IPN Progress Report 42-175 • November 15, 2008

Complete Lunar Exploration Coverage Analysis

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NASA's Vision for Space Exploration is to establish a permanent human presence on the Moon beginning no later than 2020. It is essential to provide an architecture that is expandable and evolvable to meet the current and future communication requirements for Constellation's International Space Station missions and lunar missions. This architecture includes the existing NASA ground-based and Earth-orbiting networks, as well as a possible network of lunar relay satellites. A key metric for decisions in selecting or expanding the communication infrastructure is its coverage capability. This article provides detailed coverage analysis for various phases of a lunar exploration mission, including the launches of the Crew Exploration Vehicle (CEV) and the Lunar Surface Access Module/Earth Departure Stage (LSAM/EDS), their low-Earth-orbiting operations and docking; the trans-lunar insertion of the CEV/LSAM stack, its lunar orbiting insertion and low-lunar-orbiting operations; and the LSAM descent/ascent operations, as well as the Earth return phase. The human outpost of lunar exploration is assumed to be at the lunar south pole; the top 10 landing sites suggested by *NASA's Exploration Systems Architecture Study* for lunar sortie missions are also considered. Surface-to-surface, Earth, and solar coverage at the lunar south pole using Goldstone Solar System Radar terrain data are also analyzed and discussed.

I. Introduction

The primary mission for Constellation is to carry out a series of human exploration missions ranging from low Earth orbit (LEO) to the surface of the Moon and Mars, as specified by the Vision for Space Exploration. To support Constellation missions, it is essential to provide an architecture that is expandable and evolvable to meet the current and future communication requirements for Constellation's International Space Station missions, lunar missions, and beyond. This architecture includes the existing NASA ground-based and Earth-orbiting networks, as well as a possible network of lunar relay satellites. A key metric for decisions in selecting or expanding the communication infrastructure is its coverage capability.

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, and at the Department of Mathematics at California State University, Fullerton.

This article provides detailed coverage analysis for various mission phases of a lunar exploration mission, including the launches of the Crew Exploration Vehicle (CEV) and the Lunar Surface Access Module/Earth Departure Stage (LSAM/EDS), their low-Earth-orbiting operations and docking; the trans-lunar insertion of the CEV/LSAM stack, its lunar orbiting insertion and low-lunar-orbiting operations; and the LSAM descent operations. The human outpost of lunar exploration is assumed to be at the lunar south pole, but the top 10 landing sites suggested by *NASA's Exploration Systems Architecture Study*[1] for lunar sortie missions are also considered.

The planetary ephemeris used in this article is the JPL Developmental Ephemeris DE421 for 1900–2053. Analyses were simulated using the JPL-developed Telecom Orbit Analysis and Simulation Tool (TOAST) [1] and the Communication-centric Spacecraft Design Optimization Tool [2].

The rest of the article is organized as follows: Section II describes the communication architecture elements of lunar exploration. This includes the existing space-based network, the ground-based network, and various configurations of a future network of lunar relay satellites. Section III provides a high-level description of the Constellation flight systems and a summary of chronological activities of a lunar mission, and Section IV describes the top 10 landing sites suggested by *NASA's Exploration Systems Architecture Study* for lunar sortie missions. The coverage analysis of various scenarios is discussed in Section V. Subsection V.A provides the aerial coverage of the Space Network and the ground-based networks. Subsection V.B addresses the coverage of the CEV in the Moon's vicinity by the ground-based networks. Subsection V.C discusses the coverage of the lunar orbiting assets by the ground-based networks. Subsection V.D provides the coverage of the lunar surface by the Earth-based networks and the Lunar Relay Satellite (LRS). In Subsection V.E, the radar image of the lunar south pole terrain generated by the Goldstone Solar System Radar group is used to generate high-fidelity Earth and Sun coverage in the vicinity of the Shackleton Crater rim. Section VI summarizes key results.

II. Communication Architecture Elements of Lunar Exploration

A. Earth-Orbiting Network — Space Network

The Space Network (SN), consisting of the Tracking and Data Relay Satellite System (TDRSS) and a ground segment, has been providing communications support to low-Earth-orbiting (LEO) satellites since 1983 with its nine geosynchronous Tracking and Data Relay Satellites (TDRS). The SN can track, send commands, and receive telemetry from most orbiting spacecraft. There are nine TDRS: three are available for operational support at any given time and the rest serve as backup for redundancy. The ground segment includes the White Sands Ground Terminal (WSGT) in New Mexico and the Guam Remote Ground Terminal (GRGT). The first six TDRS (F-1 through F-7; F-2 was lost with the Space Shuttle Challenger in 1986) went into service in the 1980s. Three second-generation TDRS (F-7 through F-9) began their service in the early 2000s with more advanced communications capabilities; primarily the

[1] *NASA's Exploration Systems Architecture Study*, Final Report, November 2005, NASA TM-2005-214062, is available at http://www.nasa.gov/exploration/news/ESAS_report.html or http://www.sti.nasa.gov.

higher-bandwidth Ka-band, which can transmit up to 800 Mbps, and the multiple-access capability, which can receive telemetry from five spacecraft at lower data rates and simultaneously issue commands to a single user [3]. Two additional third-generation TDRS are scheduled for replenishment in 2012 and 2013. The SN will be the primary communications provider for the CEV during its LEO phase up to the Trans-Lunar Injection (TLI), as well as the Earth return phase.

B. Ground-Based Networks — Deep Space Network and Other Ground Stations

During its round-trip journey to the Moon, the CEV will rely on ground stations for communications coverage. The current Deep Space Network (DSN) consists of ground antennas located at three sites: Goldstone in California, Canberra in Australia, and Madrid in Spain. An earlier study [4] indicated that the current DSN cannot provide continuous coverage for missions at the Moon. Communications between Earth and the Moon can be interrupted from time to time because the Moon is relatively close to Earth and because the DSN stations are neither on the equator nor are they separated by exactly 120 deg. To provide redundant communication coverage, especially for manned missions at the Moon, the DSN needs to be expanded. Simply adding more antennas to the existing DSN sites is not a sound solution, as the 37-/40-GHz (Ka-band) frequencies are quite sensitive to weather; site diversity is also a need. An earlier study [5] indicated that the DSN can be extended efficiently to support missions at the Moon by adding Hartebeesthoek in South Africa, Santiago in Chile, and Usuda in Japan. These three additional sites have existing facilities that can provide communications services to lunar craft. Most importantly, these sites complement the current DSN well, and their geometric spacing on Earth provides good site diversity; no two sites would suffer from the same adverse weather. The current DSN is denoted in this article by DSN3, and DSN6 is used to refer to the DSN plus the three additional sites: Hartebeesthoek, Santiago, and Usuda. For comparison purposes, coverage analyses are performed on both DSN3 and DSN6.

C. Lunar Relay Satellites and Satellite Constellations

NASA's Lunar Architecture Team has selected a highly elliptical orbit developed [6] as a potential candidate for the Lunar Relay Satellite (LRS). The primary objective of the LRS is to provide relay communication coverage for the lunar south pole. Figure 1 shows the orbital path of the LRS. This 718 × 8090 km orbit has an orbital period of 12 hr with a 57-deg inclination. The argument of perilune for this orbit is 90 deg, so that it spends over 70 percent of its time in the southern lunar hemisphere. It should be remarked that this orbit is practically frozen, in that both the eccentricity and the perilune–apolune line for the orbit exhibit only very diminutive librations, even without any station-keeping maneuvers. Detailed descriptions of the LRS, including the payload analysis and launch vehicles, were discussed by [7]. The first LRS is planned for launch in 2018 and the second one is scheduled for 2022. Though the size and the eccentricity of the orbit of the second LRS is identical to that of the first one, there are several options for its orientation, which leads to two relay satellite constellations. In Constellation A, both LRSs are in the same plane, but phased by 180 deg. In Constellation B, the second LRS is placed in the orthogonal plane with its apolune in the northern hemisphere. Both constellations are shown in Figure 1. Each

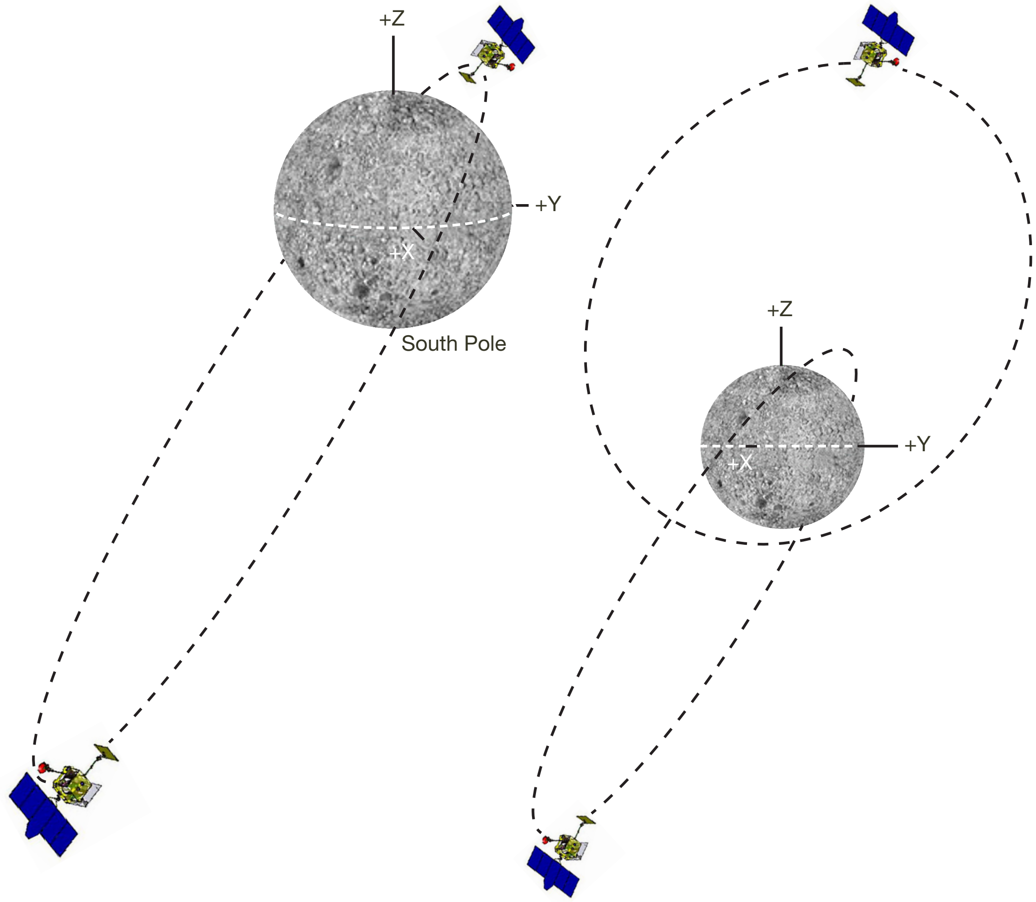


Figure 1. Trajectories and orientations of the LRS in Constellations A and B.

constellation has its own advantages, depending on the locations of exploration assets on the Moon. Constellation A would provide would provide round-the-clock coverage for the lunar south pole, while Constellation B would provide more uniform coverage globally.

For purposes of completion and comparison, two additional relay satellites in halo orbits near the Earth–Moon libration points, L1 and L2, are considered. These lunar libration relay satellites are abbreviated LLRS1 and LLRS2, respectively. Their orbital sizes and shapes are graphed to scale along with the Moon in Figure 2. The periods of these orbits are approximately 12 days for LLRS1 and 14 days for LLRS2. When correctly phased, they can provide continuous relay service to any polar region for days. However, the slant range from these satellites to a user on the lunar surface could vary from 34,000 to 84,000 km, which makes them less attractive than the LRS because a user on the lunar surface would require 12 to 20 more dB to close the link. The details of these orbits can be found in [8].

III. Flight Systems of Lunar Exploration

Flight systems of lunar exploration include the CEV, the LSAM, and the EDS. Brief functional descriptions are given next.

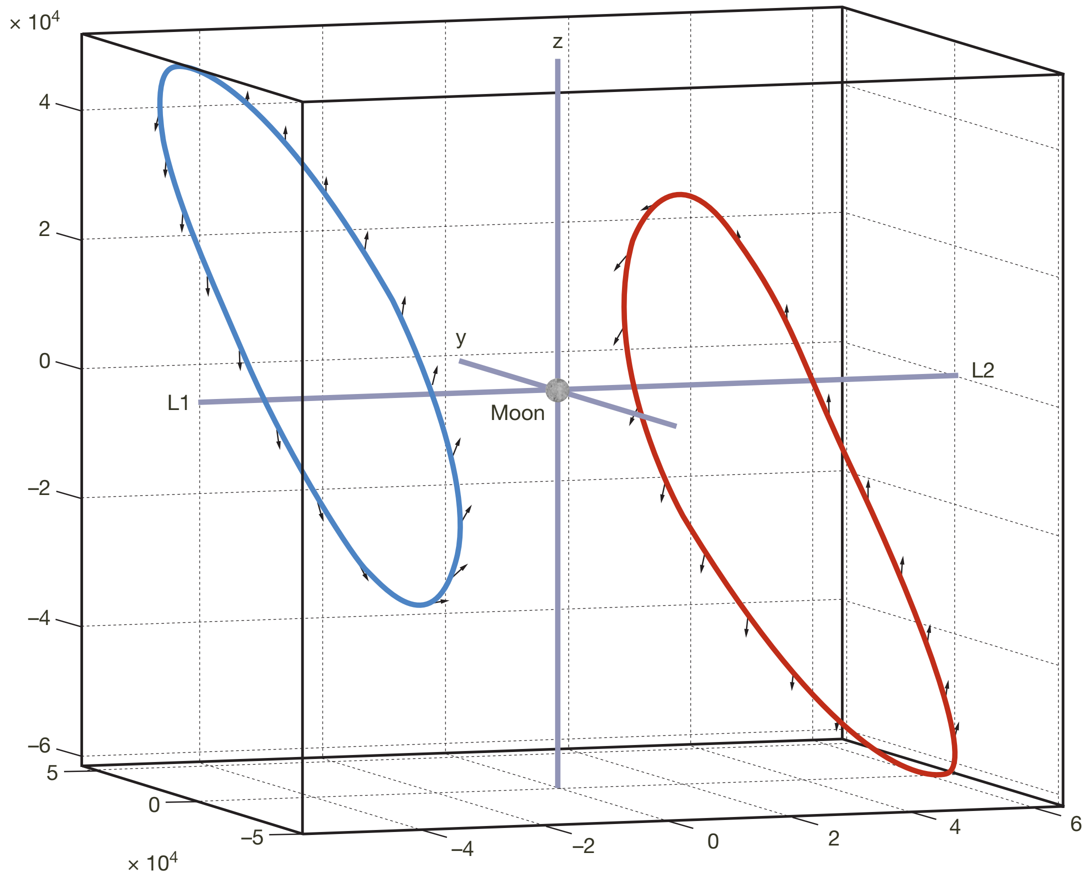


Figure 2. Trajectories of the halo orbit of the LRSs near the Moon–Earth Lagrange L1 and L2 points.

Crew Exploration Vehicle (CEV). The CEV provides the necessary crew habitation and crew health maintenance functions from launch to lunar orbit and return to Earth's surface, including possible abort during Earth ascent. The CEV will also provide the necessary propulsive accelerations to return the mission crew from lunar orbit, independent of orbital alignment, for direct entry at Earth. The CEV will rendezvous and dock with other mission elements, such as the EDS and LSAM, in both LEO and lunar orbit. In addition, the CEV will operate un-crewed in lunar orbit while the crew is on the surface of the Moon.

Lunar Surface Access Module (LSAM). The LSAM provides the necessary crew habitation, crew health maintenance, and transportation functions from lunar orbit to the lunar surface. During return to lunar orbit, the LSAM will provide crew habitation during lunar surface operations. In addition, the LSAM will provide capabilities for the crew to conduct science and perform routine extravehicular activities (EVAs) on the surface of the Moon.

Earth Departure Stage (EDS). The EDS provides the necessary propulsive accelerations needed to transfer the various flight elements (such as the CEV/LSAM stack) from LEO to the lunar vicinity.

The CEV is delivered to LEO by the Crew Launch Vehicle (CLV), and the LSAM/EDS stack is delivered to LEO by the Cargo Launch Vehicle (CaLV). The CaLV/LSAM-EDS launch precedes the CLV/CEV launch by at least a day. While in LEO, the CEV and the LSAM/EDS stack will be in circular orbit with an altitude around 330 km and inclination about 28.5 deg. The LSAM/EDS stack and the CEV will dock before the TLI burn. Once the TLI burn is completed, the EDS will be discarded. It would take the CEV/LSAM about three days to arrive at the Moon and another day to lower its orbit to a 100-km circular polar orbit before dropping off the LSAM with the astronauts to the lunar surface. To return to Earth, the astronauts use the upper unit of the LSAM to ascend from the lunar surface. The CEV will be orbiting the Moon for approximately seven days before it can rendezvous with the LSAM to pick up the crew and bring them back to Earth. The CEV will enter Earth's atmosphere in a capsule with a heatshield and parachute similar to that of the Apollo capsule. Communication coverage for the CEV or any mission element is handled primarily by the SN when it is near Earth and by the DSN when it is at higher altitudes. Figure 3 summarizes the sequential activities of the CEV on its round-trip flight to the Moon.

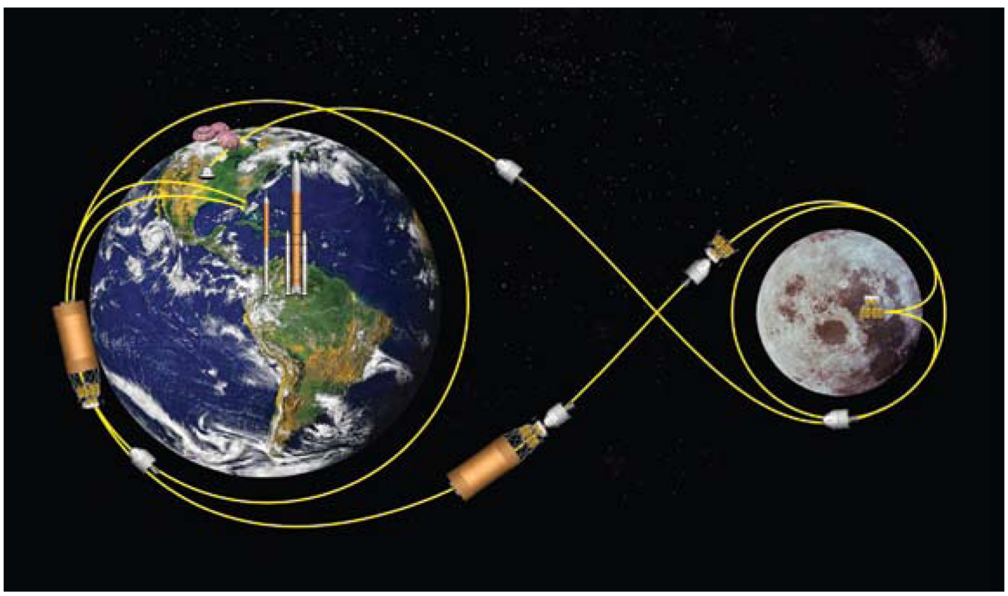


Figure 3. Design reference mission for a lunar surface exploration.

IV. ESAS Top 10 Lunar Landing Sites

NASA's Exploration Systems Architecture Study (ESAS) identified the top 10 landing sites on the Moon that are of high scientific value for lunar sortie missions. These high-priority landing sites are shown in Figure 4, with the near side enclosed by the broken-line boundaries. Four among these 10 sites are on the near side of the Moon, where direct-to-Earth communication is feasible. Two sites on the far side would rely solely on some orbiting relay asset to communicate with Earth. The remaining four landing sites, two at the poles and two at the limb, are in the zones on the Moon most sensitive to its libration, and thus they could spend days without seeing Earth.

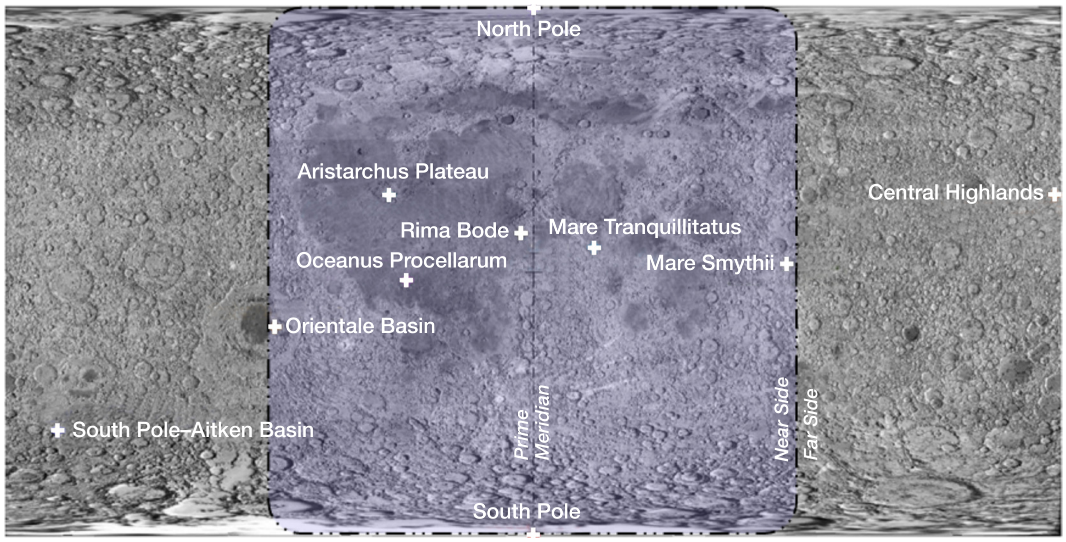


Figure 4. Ten high-priority landing sites on the Moon identified in the 2005 *NASA's Exploration Systems Architecture Study*.

V. Coverage Analysis

A. Aerial Coverage of the Space Network and the Ground Network

When the CEV is in LEO, it makes sense for the SN to provide communication coverage. The field of view (FOV) of the first-generation TDRS is a rectangle of ±22 deg east–west and ±28 deg north–south from nadir. Areas of coverage are broader for the second-generation TDRS. In particular, they can cover an elliptical FOV of ±76.8 deg east–west and ±30.5 deg north–south from nadir. The coverage contours of concentric spheres of different radii are displayed in Figure 5(a) and (b), with first-generation TDRS (F-3) and second-generation TDRS (F-9), respectively. The colors of the TDRS altitudes are shown in the figure as follows: 1000 km, red; 5000 km, yellow; 10,000 km, cyan; 20,000 km, green; and 35,000 km, blue. The areas bounded in red, yellow, and cyan colors are exclusion zones and are parts of the spheres that are either on the opposite side of TDRS or on the sides that were cut off by the rectangular FOV cone. For the 20,000 km and 35,000 km altitudes, the area immediately surrounding the TDRS is in view, and, as it spreads out, the area of coverage turns into the exclusion zone and vice versa every time it crosses the same color lines.

When the rectangular FOV cone intersects the sphere, one needs to distinguish between the same-hemisphere and opposite-hemisphere coverage, as the slant ranges for the cases are significantly different. The slant range for the opposite-hemisphere coverage could be as far as 68,000 to 84,000 km for spacecraft in the 20,000 to 35,000 km altitudes. Figure 6 shows the areas of coverage for 5000 km, 10,000 km, 20,000 km and 35,000 km. The areas shaded in green, burgundy, and blue represent same-hemisphere coverage, opposite-hemisphere coverage, and the exclusion zones, respectively. As the radius of the concentric sphere increases, the area of same-hemisphere coverage shrinks, leaving the majority of the coverage in the opposite hemisphere. As a result of almost doubling the slant range, the spacecraft would need an additional 6 dB, just on the path loss, to be able to close the link in order to communicate to a TDRS.

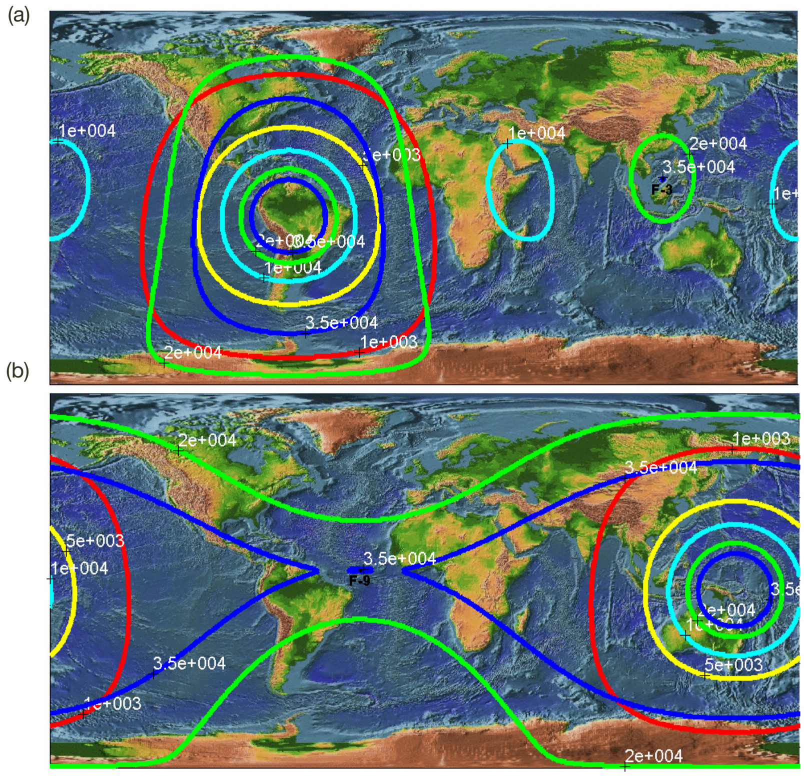


Figure 5. Aerial coverage of spacecraft in different altitudes by (a) the first-generation and (b) the second-generation TDRS.

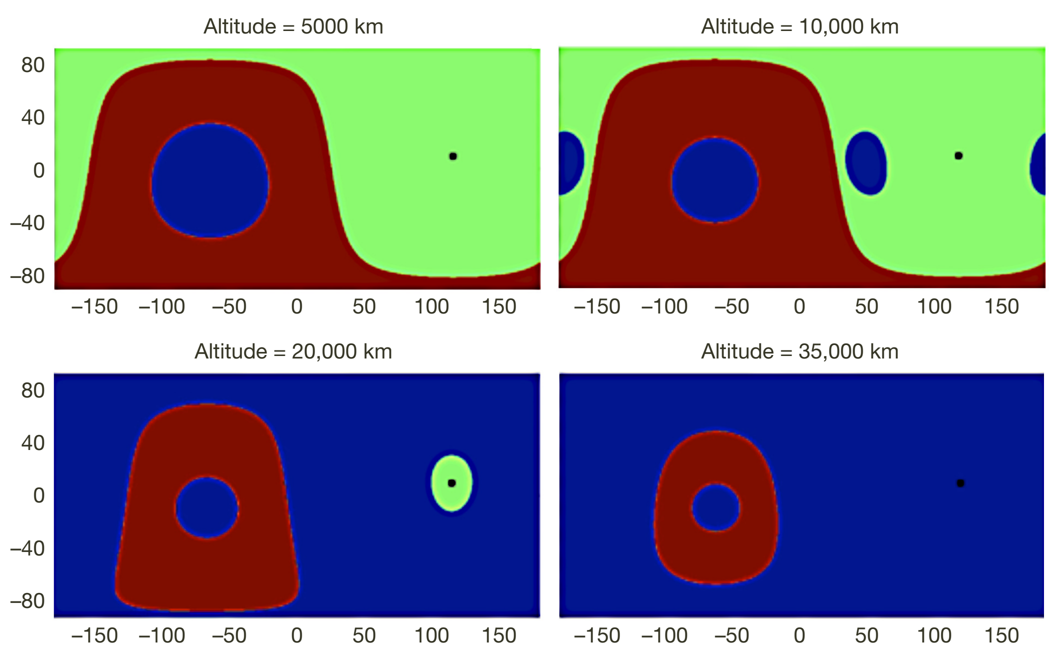


Figure 6. Same-hemisphere coverage (green), opposite-hemisphere coverage (burgundy), and zones of exclusions (blue) of a first-generation TDRS.

Next, the number of TDRS needed to provide global aerial coverage for an orbiting spacecraft at different altitudes is investigated. In particular, two scenarios are considered. The first scenario involves two TDRS (F-3 and F-9) and the second involves three TDRS (F-3, F-8, and F-9). While F-3 is the first-generation TDRS located at 115.1 deg due east, F-8 and F-9 are both second-generation TDRS and are located at 30.9 deg and 147.8 deg due west, respectively. For each combination, the same-hemisphere and opposite-hemisphere aerial coverages for a spacecraft at different altitudes are computed. For altitudes below 10,000 km, two TDRS (F-3 and F-9) are sufficient to provide 99 percent or more of the coverage; 100 percent coverage is not possible at 10,000 km due to the slight inclination of the orbital planes of TDRS. At 20,000 km altitude, two TDRS can cover up to 88 percent of the sky, and that can be improved to 98 percent with three TDRS. The aerial coverage is more limited at 35,000 km — same-hemisphere coverage is only 10 percent with two TDRS and 18.5 percent with three TDRS. The remaining results can be found in Table 1.

Table 1. Same-hemisphere, opposite-hemisphere, and total coverages of two TDRS combinations.

SN Coverage, km	F-3 & F-9, Same %	F-3 & F-9 Opposite %	F-3 & F-9, Total %	F-3, F-8, & F-9, Same %	F-3, F-8, & F-9, Opposite %	F-3, F-8, & F-9, Total %
1000	90	10	100	99.6	0.4	100
5000	90	10	100	99.6	0.4	100
10,000	87	12	99	99.5	0.5	100
20,000	34	54	88	54.5	43.5	98
35,000	10	51	61	18.5	62.5	81

Due to the tilt of Earth (23.5 deg) and the inclination of the lunar orbital plane (5.145 deg), the footprint of the Moon on Earth is bounded between a ±28.65-deg band around the equator. The size of the Moon is approximately 0.5 deg and thus the footprint of the Moon never appears beyond the ±30 deg latitudes. Figure 7 shows the aerial coverage of (a) DSN3 and (b) DSN6 for different altitudes. The horizontal rules mark the ±30 deg latitudes. The color-coded contours represent the visible areas by the ground stations for altitudes above: 1000 km, red; 5000 km, yellow; 10,000 km, cyan; 20,000 km, green; 30,000 km, blue; 35,000 km, white (altitude of TDRS); 40,000 km, magenta; and 400,000 km, black (approximately farthest Earth–Moon distance). With the 10-deg elevation mask, there are areas DSN3 cannot cover; specifically, when the Moon is over Argentina, the Indian Ocean part east of Madagascar, or Myanmar. The zones of exclusion are larger for DSN3 when the spacecraft is on its way to the Moon. For example, the green "mouth" of the "smiling face" in Figure 7(a) depicts the noncoverage area for spacecraft that are at 20,000 km or below. Such a noncoverage region is annihilated when DSN6 is considered. Hartebeesthoek wipes out the largest DSN3 noncoverage region over the southern Indian Ocean. Santiago and Usuda help in bridging the communication gaps over Argentina and Myanmar, respectively.

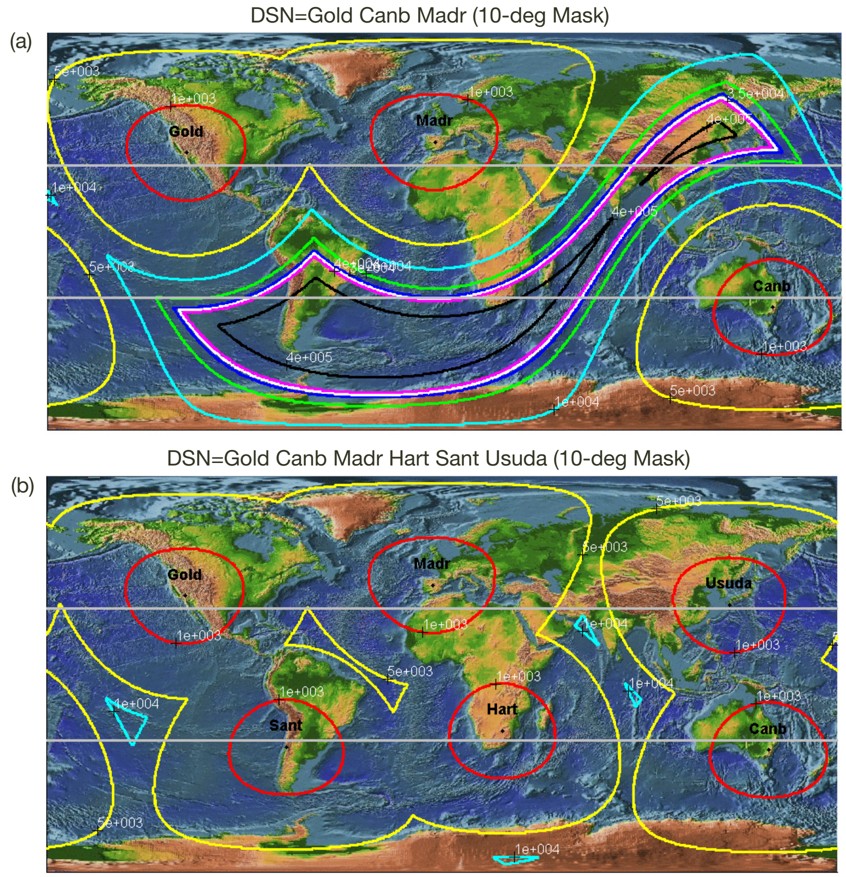


Figure 7. Aerial coverage of spacecraft in different altitudes by the ground networks (a) DSN3 and (b) DSN6.

The aerial coverage by both the SN and DSN3/DSN6 is summarized in Figure 8, which indicates that the suitable altitude to switch from SN to DSN6 is at 10,000-plus km. When a spacecraft is below such an altitude, two TDRS (F3 and F9) are sufficient to cover it; when it is higher, it is covered by DSN6.

A. Coverage of the CEV in the Lunar Vicinity by DSN3/DSN6

Ground network coverage for a typical round-trip trajectory of the CEV to the Moon is analyzed in this subsection. The altitudes of the CEV throughout the 20-day journey, including the major maneuvers, are shown in Figure 9. In general, after launch the CEV remains in a 330-km circular orbit and then performs a TLI burn roughly a day after. The CEV spends four days in Trans-Lunar Cruise (TLC) and arrives at the Moon in a plane perpendicular to the Earth–Moon line. After performing Lunar Orbit Insertion (LOI) and lowering itself to a 100-km circular polar orbit, the CEV spends approximately seven to eight days orbiting the Moon. By this time, the orbital plane of the CEV is edge on with the Earth-Moon line. Finally, a series of three Trans-Earth Injection (TEI) burns will put the CEV on its path back to Earth. One should note that the timeframe for this mission is in March, and as a result the footprints of the Moon and the CEV in the vicinity of the Moon will appear over the southern latitudes on Earth. Therefore, communication gaps between the CEV and DSN3 can only happen when the footprints of the CEV cross the wedges of exclusion over the

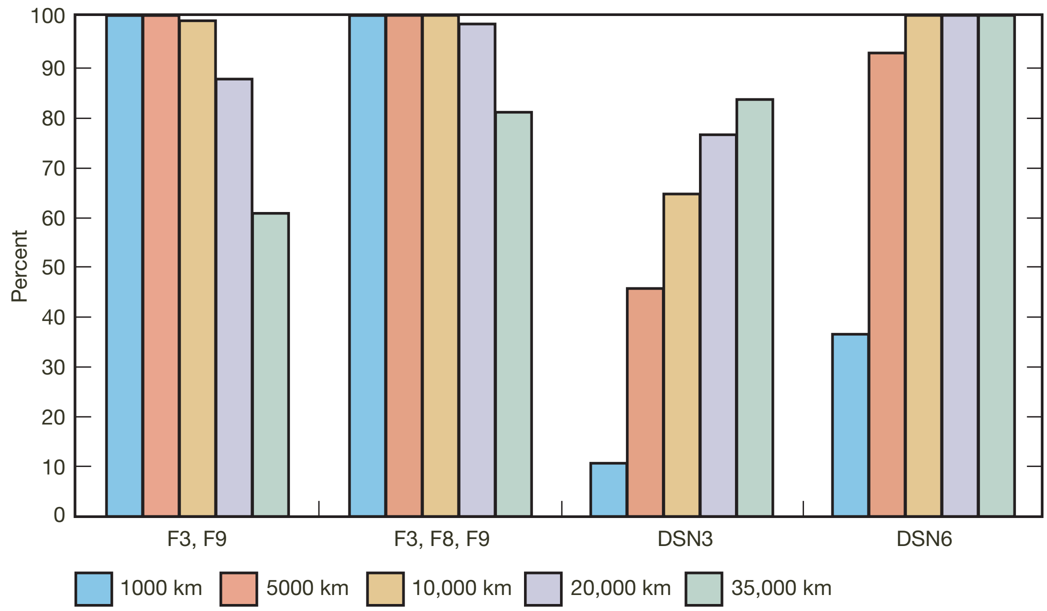


Figure 8. Aerial coverage percentage for spacecraft at different altitudes by the SN, DSN3, and DSN6.

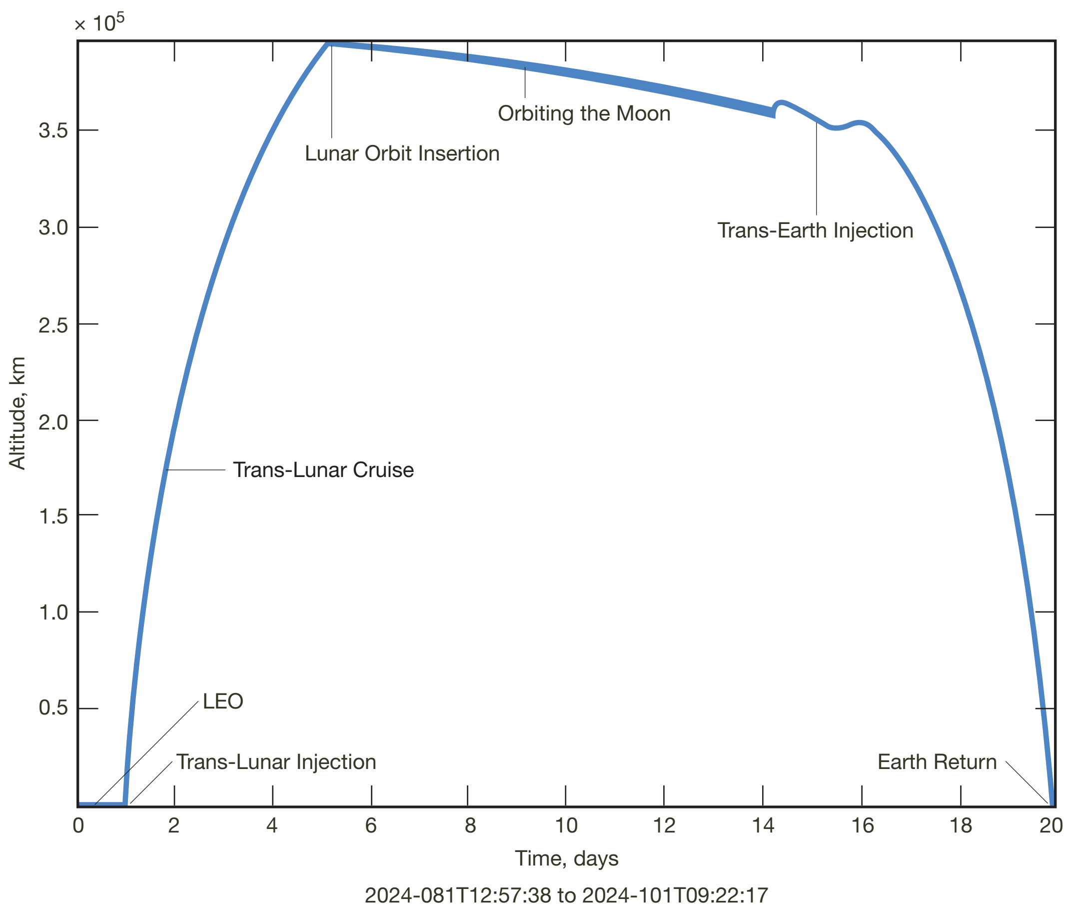


Figure 9. Altitudes of the CEV during the 20-day round-trip journey to the Moon.

southern Indian Ocean and Argentina. Also, when the CEV arrives at the Moon, the Moon is at approximately 400,000-km altitude, and when the CEV is performing the TEI burns to return to Earth, the Moon is at perigee, or is closest to Earth at roughly 365,000 km away.

The ground network coverage of the CEV on its way to the Moon is discussed next, focusing on the 4-day period from TLI until LOI. Figure 10 shows the first 8 hr after the TLI burn. When the CEV is in its circular 330-km orbit, the TLI burn starts over the west coast of Central Africa and lasts for 5 min. The five orange dots in the global Earth map represent the footprint of the CEV during TLI burn. The CEV heads in the southeast direction. The subsequent four gray dots show that the CEV is continuing to climb to 1000-km altitude. Colors specifying higher altitudes for the CEV are described as follows: 1000 km to 5000 km, red; 5000 km to 10,000 km, yellow; 10,000 km to 20,000 km, cyan; 20,000 km to 30,000 km, green; and 30,000 km to 100,000 km, blue. At times, the CEV can dip as low as 30 deg southern latitude in the first hour, but remains above 20 deg latitude for the rest of the TLC period. Thus, communication between DSN3 and the CEV during this period can only be interrupted when the footprints of the CEV appear in the exclusion wedge in the southern Indian Ocean between Canberra and Madrid. It will take the CEV 9 and 39 min to reach altitudes of 1000 km and 10,000 km, respectively. There is no contact between DSN3 the CEV for more than 29 min after the TLI. The first DSN3 station to make contact with the CEV is Canberra. The CEV appears to reserve its course westward 2 hr after the TLI because the CEV is dashing for the Moon as Earth is rotating beneath it. The first contact between Canberra lasts more than 6 hr, and, because the CEV is still near Earth, the first gap between Canberra and Madrid lasts more than 68 min. As expected, the daily gap is shortening as the CEV gets closer to the Moon; in particular, the remaining gaps during the TLC are 25, 18, and 14 min sequentially. For this particular mission segment, adding the Hartebeesthoek site to DSN3 will bridge the four daily communication gaps between Canberra and Madrid. More importantly, it will shorten the wait time for the first contact between the ground network and the CEV after the TLI burn. Specifically, the first 29-min gap between the CEV and the DNS3 after TLI is broken down as follows: Eight minutes into TLI, Hartebeesthoek can have the first contact with the CEV and the contact lasts approximately 17 min, after which there is another 5-min gap. Similar ground coverage for the CEV immediately post-separation using other ground network antennas was also studied (see [9] for details).

Coverage analysis for the CEV when it is orbiting the Moon appears in the next subsection where coverage of the DSN3/DSN6 for all lunar orbiting assets is discussed. For the moment, we will concentrate on the coverage of the CEV during its Earth return phase, which takes approximately 5.33 days. The footprint of the CEV on its way back to Earth is plotted in the global Earth maps of Figure 11. The colors show the current altitude of the CEV. The magenta dots are the footprint of the CEV when its altitude is between 385,000 km and 250,000 km. Each transverse line takes approximately one day and it would take the CEV over 3.75 days to depart the Moon's vicinity to 250,000 km altitude and another 1.25 days to descend to 100,000 km altitude. When the altitude of CEV is between 250,000 km and 100,000 km, its footprint is plotted in white. Dots in other altitudes follow the same color code as those in Figure 10. The altitude and elevation angles at the specific ground sites are displayed on the top of Figure 11. The first two TEI burns (5.5 and 2 min long) are separat-

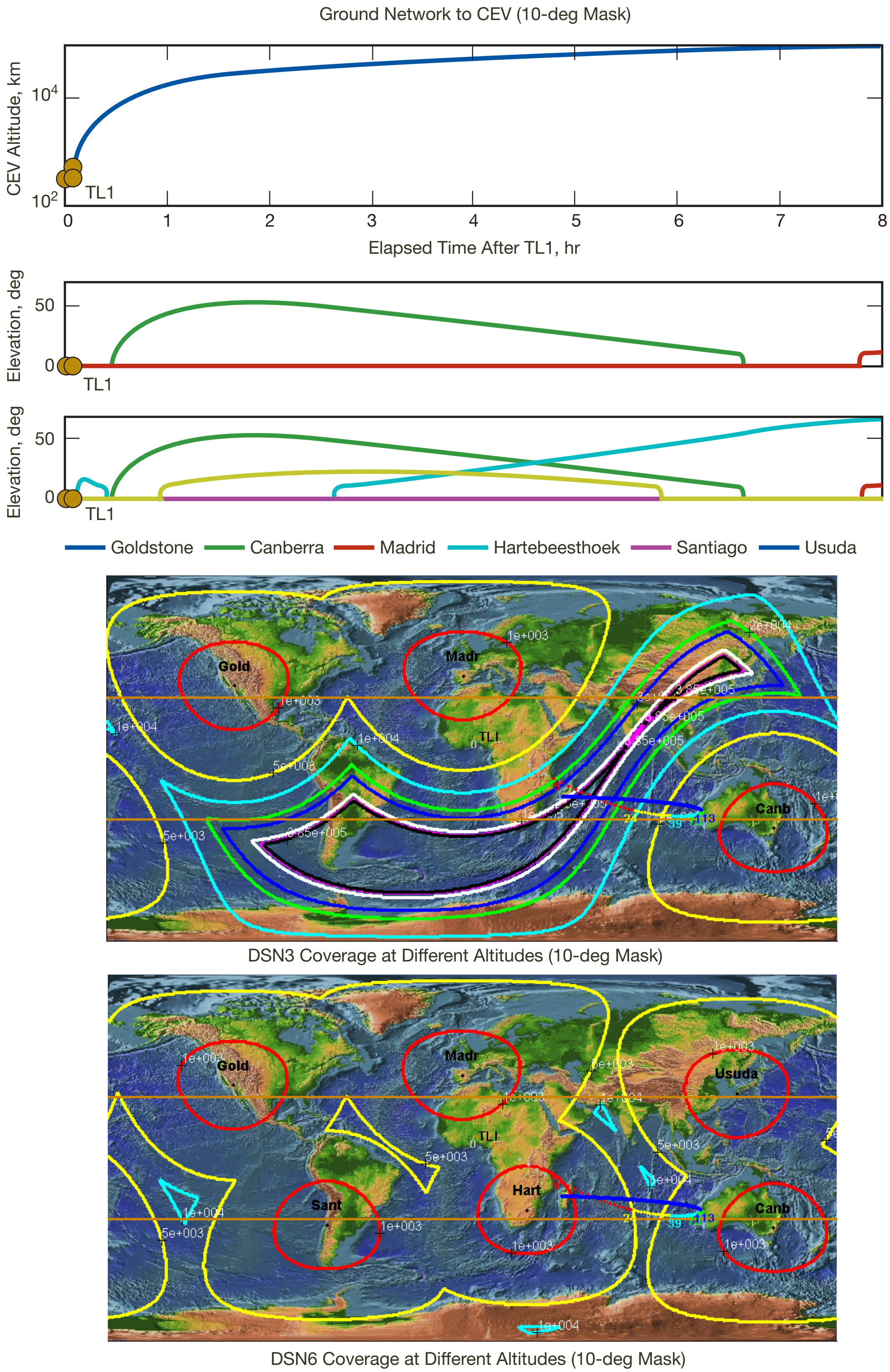
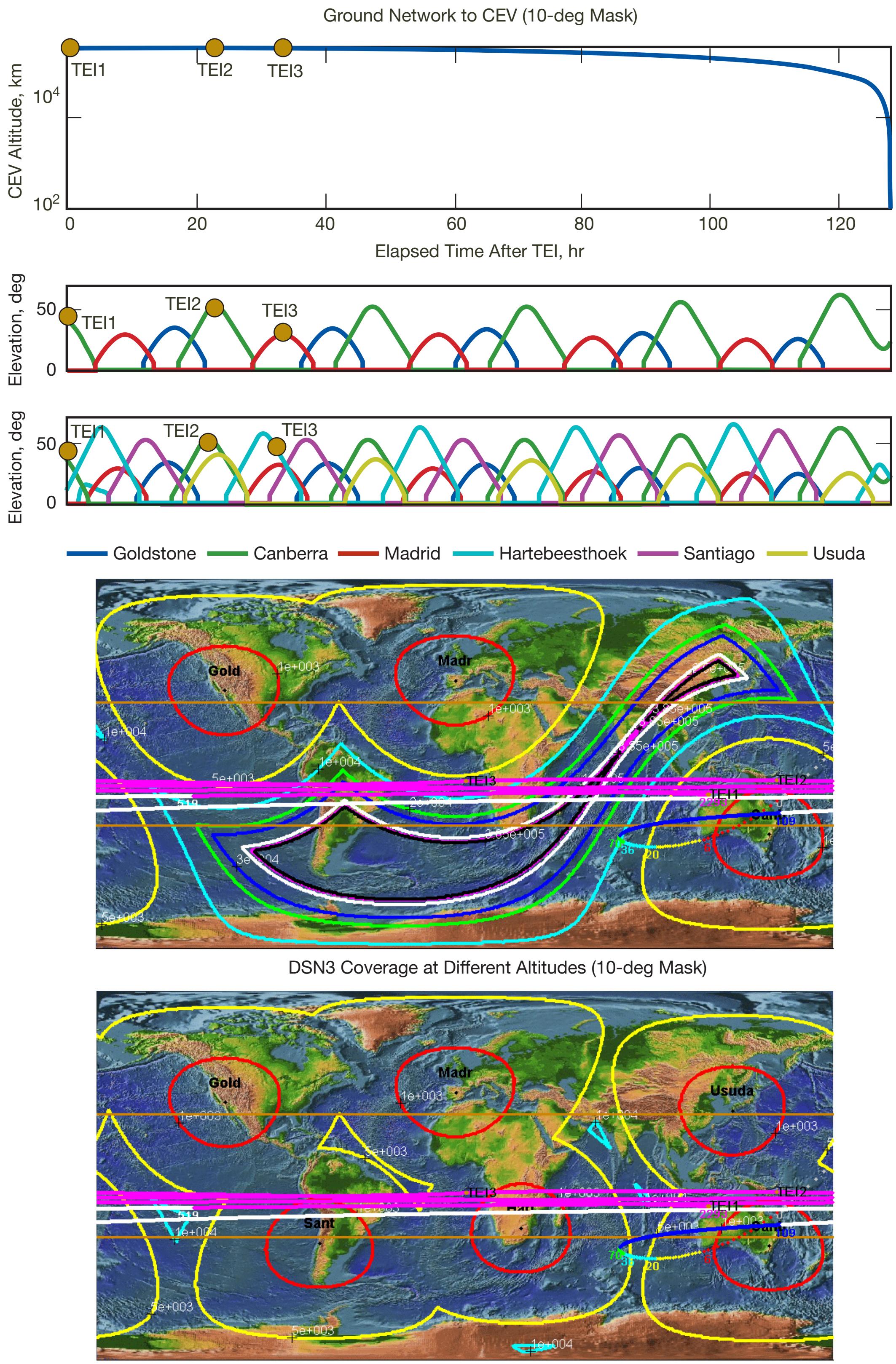


Figure 10. The CEV's altitudes and elevation angles at specific ground sites, and footprint of the CEV and aerial coverage of the ground network (DSN3 and DSN6) during the first 8 hr after the TLI burn.



DSN3 Coverage at Different Altitudes (10-deg Mask)

DSN6 Coverage at Different Altitudes (10-deg Mask)

Figure 11. The CEV's altitudes and elevation angles at specific ground sites, and footprint of the CEV and aerial coverage of the ground network (DSN3 and DSN6) during the Earth return phase.

ed almost one day apart. The final TEI burn (3 min long) is 10 hr after that. At precisely the TEI burns, both DSN3 and DSN6 are in view with the CEV. The daily gaps between the CEV and DSN3 will continue to happen. The gaps during the handover between the Canberra and Madrid stations are 20, 12, 18, 24, and 37 min consecutively. Until the last day of the return flight, there are two additional gaps: a 3-min gap between Madrid and Goldstone and a 5-min gap between Canberra and Madrid. DSN6 can cover the CEV for practically the entire Earth return phase until the last 5.2 min, when the CEV's altitude drops below 1000 km. In all, DSN6 will not only provide consistently better coverage than DSN3, but its coverage also does not depend on the trajectory path of the CEV or the mission timeframe.

C. Coverage of the Lunar Relay Orbiting Assets by DSN3/DSN6

This subsection discusses the direct-to-Earth coverage for the lunar relay orbiting assets, which include the LRS, Constellation A, Constellation B, LLRS1, LLRS2, and the CEV. The exact values can be found in Table 2. The information in Table 2 should be interpreted in the following manner: The units for the contacts and gaps are in hours. The set of three values, for example, in the "Contacts" row, describes the minimum, average, and maximum contacting times of the passes. The coverage value is the percentage of time.

Table 2. Contacts, gaps, and coverage information between DSN and lunar relay orbiting assets.

Lunarcraft		Direct to Earth					
		DSN3			DSN6		
		Minimum	Average	Maximum	Minimum	Average	Maximum
CEV (in circular 100-km polar orbit)	Contacts, hr	0.0167	1.69	31	1.18	1.82	75.3
	Coverage, %		72.3			73.2	
	Gaps, hr	0.0167	0.646	1.32	0.0667	0.663	0.783
LRS	Contacts, hr	0.175	14.6	101	11.1	33.1	238
	Coverage, %		96.49			97.6	
	Gaps, hr	0.025	0.448	1.4	0.025	0.448	1.4
Constellation A	Contacts, hr	7.15	38.2	348		Continuous	
	Coverage, %		99.04			100	
	Gaps, hr	0.025	0.285	0.65		No gap	
Constellation B	Contacts, hr	7.5	45.4	347		Continuous	
	Coverage, %		99.25			100	
	Gaps, hr	0.025	0.274	0.625		No gap	
Lunar Halo at LL1	Contacts, hr	6.55	21.6	25.5		Continuous	
	Coverage, %		98.8			100	
	Gaps, hr	0.0167	0.253	0.783		No gap	
Lunar Halo at LL2	Contacts, hr	5.73	25	299		Continuous	
	Coverage, %		97.8			100	
	Gaps, hr	0.0167	0.607	1.48		No gap	

The orbital period for the CEV is almost 2 hr, of which, more than 72 percent of the time, the CEV can communicate with Earth. The communication gaps happen either when the CEV is behind the Moon or when none of the DSN stations can see the CEV. The average gap is 39 min. With DSN3, the largest gap could be as long as 79 min, but with DSN6, no gap is longer than 47 min. The CEV can see Earth at every orbit with an average contact of approximately more than 100 min. Twice a month, the CEV's orbital plane is perpendicular to the Earth–Moon line, during which the CEV could have continuous coverage with Earth for as long as 31 hr with DSN3 and 75.3 hr with DSN6.

Since the orbit of the LRS is highly elliptical and is 12 hr long, the LRS spends only a small percentage of time behind the Moon. Indeed, over 96.5 percent of the time the LRS is in view with Earth and it stays on the average 27 min behind the Moon. The longest time it can be out of view with DSN3 is 1.4 hr. Again, there are two periods per month when Earth can see the entire orbit of the LRS. During such periods, continuous contacts could be as long as 4 days with DSN3 and close to 10 days with DSN6.

Due to the design, one of the relay satellites in Constellation A or B can always be in view with Earth, and thus, DSN6. More than 99 percent of the time, one of the three DSN stations can see the Constellations. Some communication gaps between DSN3 and the Constellations do occur; however, they are 17 min long on average with no gaps longer than 39 min.

DSN6 can always see the halo orbits near the Earth–Moon libration point for the following reasons: The orbit of LLRS1 is between Earth and the Moon, so nothing is obstructing it from Earth. As for LLRS2, though behind the Moon, its halo trajectory is quite inflated and thus the Moon never blocks it from Earth. On the other hand, the communication gaps between DSN3 and the lunar halo orbits are longer because the satellites in these orbits are moving slower and more broadly compared to the LRS.

D. Coverage of the Lunar Surface Assets

A lunar surface asset (LSA) could be a rover, an astronaut, an outpost, or a lunar communications tower (LCT). To communicate with Earth, an LSA can do so directly or via a relay satellite, when the line of sight can be established. Figure 12 displays the different means by which an LSA connects with Earth. The dotted green lines show direct communications with Earth, while the yellow lines show feasible options for data being sent to an orbiting asset for storage and later forwarding to Earth; the dotted red lines connect an LSA to Earth using the direct-bent-pipe (DBP) mode, in which case the data are fed forward instantly.

The next focus is on the coverage of any LSA at the top 10 landing sites on the Moon as given by ESAS. Keep in mind that the coverage analysis assumes that the horizon elevation mask angle for an LSA is 3 deg. Table 3 details the coverage analysis for the 10 landing sites in direct-to-Earth (DTE) and store-and-forward modes. The landing sites are listed in descending order according to the latitudes. The regions of the landing sites are also specified. The minimum, mean, and maximum values for the contacts and gaps are in the format identical to those defined in Table 2.

The DTE links involve either DSN3 or DSN6. The four sites on the near side of the Moon are continuously in view with DSN6, but out of DSN3's view for an average of 15 min each time, with the largest gap not longer than 38 min. The longitude of Mare Smythii is

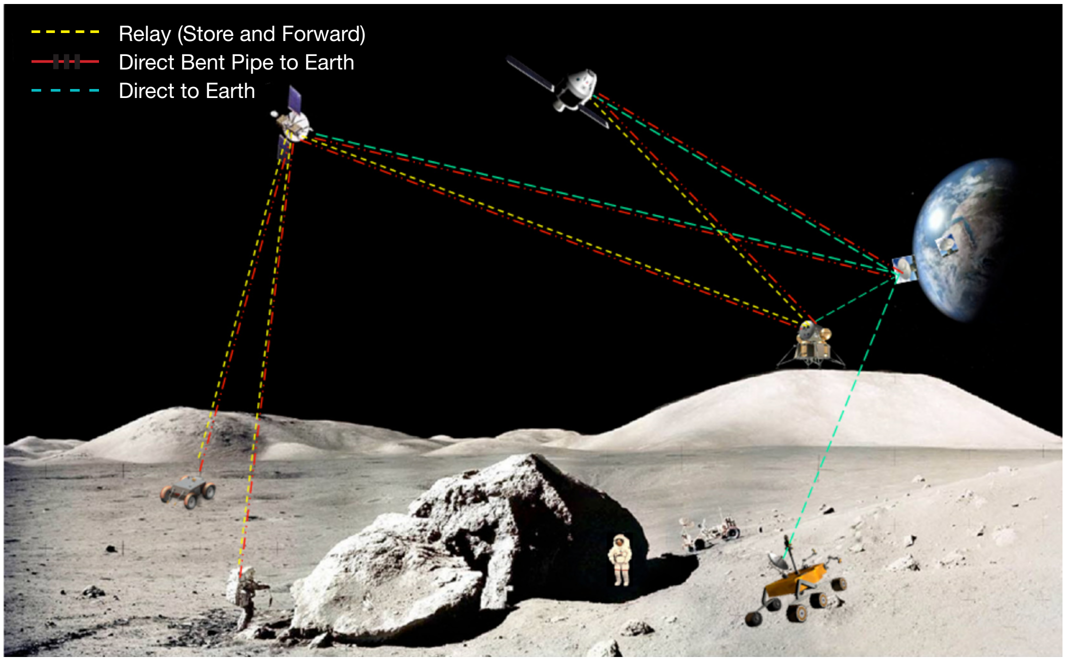


Figure 12. Communications between a lunar surface asset and Earth.

86.5 deg due east; thus, it can see Earth more than 50 percent of the time. The Orientale Basin's longitude is at 88 deg due west, which is why Earth can see it approximately 40 percent of the time. Each lunar polar region can see Earth 32 to 37 percent of the time, and, depending on its local horizon mask, it could spend one to three weeks without any view to Earth.

The relay orbiting asset in the store-and-forward mode could be the LRS, Constellation A, Constellation B, CEV, LLRS1, or LLRS2. Both LRS and Constellation A provide preferable coverage for the southern lunar hemisphere. The farther south the latitude of a landing site is, the more coverage percentage it gets. For a 12-hr period, while the north pole gets less than half an hour of coverage, the south pole receives over 9 hr of coverage from the LRS. The coverage percentage is nearly doubled or soars to 100 percent under Constellation A.

Constellation B spreads the coverage uniformly over the Moon. However, the orbits are highly elliptical and the apolunes are in the opposite poles, and the satellites spend more time at the polar regions. With just the LRS alone, the north pole would have to wait more than 11.5 hr between passes. Under Constellation B, the gap is trimmed down to 75 min. Similarly, landing sites at Aristarchus Plateau (near side) and the Central Highlands (far side) could spend up to 4 days without any contact with the LRS, and Constellation B can help to cut the worst gap down to no more than 10.6 hr.

Although not designated, for comparison purposes the CEV as a relay orbiting asset in the store-and-forward mode is also considered. Since its orbit is a low lunar polar orbit, the CEV has more frequent short contact with the poles. In particular, there is a 10-min pass every 2 hr. The CEV can also have contacts with other landing sites; however, the passes are relatively briefer and the communication gaps could be as long as 9 to 11 days.

Table 3. Communications between a lunar surface asset in DTE and store-and-forward modes.

			Earth (DTE)						Lunar Orbiter (Store and Forward)																							
Region	Lunar Site		DSN3			DSN6			LRS			Cons A			Cons B			CEV			Halo LL1			Halo LL2		
Polar	North Pole	Contacts, hr	0.38	28.8	98.4	0.38	121	248	0.48	0.48	0.5	0.48	0.48	0.5	0.48	4.77	9.07	0.17	0.18	0.18	175	175	175	81.8	81.8	81.8
		Coverage, %		35			36.9			3.98			7.97			79.6			9.04			60.8			24.5	
		Gaps, hr	0.03	44.4	422	0.18	187	412	11.5	11.5	11.5	5.5	5.52	5.52	1.2	1.23	1.25	1.78	1.79	1.8	114	114	114	245	245	245
Near	Aristarchus Plateau	Contacts, hr	7.32	27.4	123		Continuous		0.5	1.85	3.1	0.48	1.85	3.1	0.5	5.36	10.8	0.02	0.14	0.18	207	207	207	65.5	65.5	65.5
		Coverage, %		99.2			100			13.3			26.6			55.5			1.44			71.8			19.6	
		Gaps, hr	0.03	0.23	0.6	0	0	0	8.97	12.1	102	2.92	5.11	90.7	0.03	4.32	10.5	1.78	8.97	264	82.5	82.5	82.6	261	261	261
Far	Central Highlands	Contacts, hr	0	0	0	0	0	0	0.08	1.84	3.1	0.08	1.84	3.12	0.48	5.38	10.8	0.02	0.14	0.18	0	0	0		Continuous	
		Coverage, %		0			0			13.2			26.5			55.4			1.44			0			100	
		Gaps, hr		No contact			No contact		8.97	12.1	102	2.92	5.12	91.1	0.03	4.3	10.6	1.78	9.66	265		No contact		0	0	0
Near	Rima Bode	Contacts, hr	7.32	27.6	123		Continuous		0.1	3.47	6.67	0.05	3.81	69.4	0.1	6.03	10.8	0.02	0.14	0.18		Continuous		0	0	0
		Coverage, %		99.2			100			26.5			52.8			57.3			1.3			100			0	
		Gaps, hr	0.03	0.23	0.6	0	0	0	6.07	9.61	60.2	0.03	3.41	48.2	0.08	4.52	10.1	1.78	10.5	270	0	0	0		No contact	
Near	Mare Tranquillitatis	Contacts, hr	7.3	28	123		Continuous		0.08	4.1	7.7	0.08	5.11	149	0.08	6.28	10.8	0.02	0.14	0.18		Continuous		0	0	0
		Coverage, %		99.2			100			29.9			56.9			57.8			1.33			100			0	
		Gaps, hr	0.03	0.23	0.63	0	0	0	4.85	9.62	84.4	0.03	3.87	78.4	0.43	4.61	9.95	1.78	10.7	270	0	0	0		No contact	
Limb	Mare Smythii	Contacts, hr	0.4	19.5	75.6	0.08	54.8	361	0.13	4.63	8.27	0.13	5.84	197	0.28	6.36	10.9	0.02	0.14	0.18	142	142	142	145	145	145
		Coverage, %		51.8			54.3			33			60.3			58.1			1.29			48.6			44.9	
		Gaps, hr	0.03	18.4	320	0.05	55.9	315	4.12	9.47	108	0.03	4.2	96.6	0.45	4.63	9.55	1.78	10	272	148	148	148	181	181	181
Near	Oceanus Procellarum	Contacts, hr	7.3	28.4	123		Continuous		0.23	5.19	8.62	0.13	7.74	233	0.08	6.38	10.8	0.02	0.14	0.18	219	219	219	59	59	59
		Coverage, %		99.2			100			35.7			63.2			58			1.29			75.9			17.6	
		Gaps, hr	0.03	0.24	0.63	0	0	0	3.7	9.3	121	0.05	4.49	109	0.45	4.61	9.75	1.78	9.98	272	70.4	70.4	70.4	267	267	267
Limb	Orientale Basin	Contacts, hr	0.28	17.7	123	0.28	26	274	0.7	6.35	9.1	0.58	12.8	329	0.3	5.61	10.9	0.02	0.14	0.18	127	127	127	168	168	168
		Coverage, %		36.7			40.6			42.9			70.9			55.6			1.37			43.5			51.3	
		Gaps, hr	0.03	26.1	439	0.18	38.4	417	3.1	7.96	121	0.03	4.67	116	0.05	4.46	10.4	1.78	9.46	268	162	162	162	158	158	158
Far	South Pole–Aitken Basin	Contacts, hr	0	0	0	0	0	0	6.67	8.17	9.35		Continuous		0.2	5.08	9.35	0.02	0.14	0.18	50.1	50.1	50.1	259	259	259
		Coverage, %		0			0			68.1			100			73.4			2.24			17.1			79.8	
		Gaps, hr		No contact			No contact		2.75	3.83	4.97	0	0	0	0.13	1.84	4.67	1.78	6.08	228	239	239	239	67.6	67.6	67.6
Polar	South Pole	Contacts, hr	1.45	22.3	59.5	2.82	116	234	9.05	9.07	9.07		Continuous		0.48	4.77	9.07	0.17	0.18	0.18	93.5	93.5	93.5	224	224	224
		Coverage, %		32.4			35.9			75.6			100			79.6			9.05			32			69.4	
		Gaps, hr	0.03	46.5	436	0.35	187	421	2.92	2.93	2.95	0	0	0	1.2	1.23	1.25	1.78	1.79	1.8	196	196	196	102	102	102

As for the lunar halo orbits in the considered orientations, the LLRS1 spends more time in the northern hemisphere, while the LLRS2 lingers most of the time in the southern hemisphere. The order of the orientation can be reversed depending on the regions of service. It should be remarked that the coverage values from these halo orbits are relatively periodic. LLRS1 can provide uninterrupted support to the north pole for over 7 days and then goes out of sight for close to 5 days before the next view period. The landing sites on the near side of the Moon receive a very high coverage percentage, especially equatorial regions near the prime meridian. Coverage percentages for landing sites at the lunar limb regions are in the high 40s. Surprisingly, the South Pole–Aitken Basin, which is on the far side of the Moon, also gets some coverage from LLRS1 due to its location (162 deg west and 54 deg south). As expected, its temporal coverage percentage is 17 percent. The scenario is rather reversed for LLRS2. The lunar south pole can have nonstop access to the LLRS2 for over 9 days every 14 days. Except for Rima Bode and Mare Tranquillitatis, which are on the near side of the Moon and near the equator, the remaining sites do get some contacts with LLRS2. Coverage values can be found in Table 3.

The last mode of communications an LSA can have with Earth is the DBP mode. This is possible only when both lines of sight between the relay orbiting asset to Earth and to the LSA are established. This form of communications is often needed during a critical event such as descent, landing, ascent, or joy-sticking a rover from Earth. Table 4 provides the DBP coverage metrics from an LSA to DSN3 or DSN6 via one of the relay orbiting assets. These values are not a product of coverage percentages, but rather are obtained from direct numerical simulations.

E. Coverage for the Lunar South Pole Using GSSR Terrain Data

The Goldstone Solar System Radar (GSSR) group recently released a radar image of the lunar south pole [10]. The upper left portion of Figure 13 displays the elevations of an area of 480 × 680 km at the resolution of 40 m per pixel. The range of the elevations varies approximately between ±6000 m. Areas in radar shadows are designated with the value of –10,000 m and are mapped in blue or white. Of particular interest within the elevation map is the red rectangle surrounding the Shoemaker and the Shackleton craters. The floors of these craters, shown in the upper right of Figure 13, are kept in permanent darkness at extremely cold temperatures. As a result, any water molecules deposited by a comet would be well preserved. In addition, instruments on board the Lunar Prospector showed that the concentration of hydrogen at the floors of these craters was higher compared to that of the average lunar surface. In our coverage analysis, we specifically focus on the rim of Shackleton Crater, shown at the bottom of Figure 13, which stays sunlit more constantly and has been proposed as a future lunar exploration site by NASA [11]. Even though a nearby area is of a higher elevation (1700 m) than the selected strip (1000 m), it was not considered because it is located farther toward the far side and is surrounded by torturous terrain, thereby making its accessibility to the floor of the Shackleton Crater very challenging.

Next, the coverage for the highest point on the strip of Shackleton Crater's rim is investigated. The peak is located at –89.6328 deg in latitude and 160.388 deg due west in longitude. Its elevation is 1072 m above the lunar surface.

For the line-of-sight (LOS) surface-to-surface coverage, the height of the receiver is assumed to be 2 m — approximately the height of an astronaut or a rover. Figure 14 shows the LOS coverage from a 10-m tower located at the peak at the rim (a) and on the slope (b) of Shackleton Crater. The tower is shown as a bold dot in black in (a) and the lunar south pole can be seen at the upper right corner of (b) in green. The dotted circle represents the 6-km area around the tower. The visible areas are illuminated in magenta, whereas the areas without the LOS are highlighted in gold. Coverage percentages for the areas inside the 6-km radius and the 8 × 20 km rectangle are displayed.

It should be remarked here that the local peak does not necessarily yield the highest area of LOS coverage. Indeed, Figure 14(a) shows that the LOS between the 10-m tower and most of the area on both sides of the rim are blocked. This can be illustrated as follows: Imagine a person standing on a plateau at the top of a cliff that overlooks the whole valley beneath it. As soon as this individual backs away from the edge, certain areas at the foot of the cliff disappear immediately. As he/she moves farther away from the edge, a larger the portion of

Table 4. DBP coverage between a lunar surface asset and Earth.

			Direct Bent Pipe											
			via LRS		via Constellation A		via Constellation B		via CEV		via Halo LL1		via Halo LL2	
Region	Lunar Site		DSN3	DSN6	DSN3	DSN6	DSN3	DSN6	DSN3	DSN6	DSN3	DSN6	DSN3	DSN6
Polar	North Pole	Contacts, hr	0.03 0.47 0.5	0.48 0.48 0.5	0.03 0.47 0.5	0.48 0.48 0.5	0.03 4.11 9.07	0.48 4.77 9.07	0.02 0.17 0.18	0.02 0.18 0.18	0.92 21.5 25.5	175 175 175	4.83 24.1 74.3	81.8 81.8 81.8
		Coverage, %	3.95	3.98	7.9	7.97	78.9	79.6	8.94	9.02	60.4	60.8	24.4	24.5
		Gaps, hr	0.1 11.5 11.9	11.5 11.5 11.5	0.03 5.47 5.97	5.5 5.52 5.52	0.03 1.1 1.6	1.2 1.23 1.3	0.02 1.79 3.77	1.78 1.79 1.8	0.02 14.8 115	114 114 114	0.02 57.7 245	245 245 245
Near	Aristarchus Plateau	Contacts, hr	0.05 1.72 3.1	0.5 1.85 3.1	0.05 1.73 3.1	0.48 1.85 3.1	0.08 4.51 10.8	0.5 5.36 10.8	0.02 0.17 0.18	0.02 0.14 0.18	0.3 20.8 25.5	207 207 207	0.6 19.8 29.7	65.5 65.5 65.5
		Coverage, %	13.2	13.3	26.4	26.6	55	55.5	1.43	1.44	71.1	71.8	19.6	19.6
		Gaps, hr	0.03 11.3 102	8.97 12.1 102	0.03 4.82 90.7	2.92 5.11 90.7	0.03 3.7 10.5	0.03 4.32 10.5	0.02 8.99 264	1.78 8.97 264	0.02 8.78 82.6	82.5 82.5 82.6	0.02 65.3 261	261 261 261
Far	Central Highlands	Contacts, hr	0.03 1.05 3.1	0.08 1.1 3.1	0.03 1.05 3.12	0.08 1.1 3.12	0.03 3.33 10.8	0.03 3.72 10.8	0 0 0	0 0 0	0 0 0	0 0 0	5.73 25 299	Continuous
		Coverage, %	11	11.2	22.1	22.5	51.3	51.6	0	0	0	0	97.8	100
		Gaps, hr	0.03 8.45 102	0.13 8.73 102	0.03 3.69 91.1	0.05 3.81 91.1	0.03 3.13 10.6	0.05 3.45 10.6	No contact	No contact	No contact	No contact	0.02 0.61 1.48	0 0 0
Near	Rima Bode	Contacts, hr	0.05 3 6.67	0.1 3.47 6.67	0.05 3.29 24.4	0.05 3.81 69.4	0.08 4.91 10.8	0.1 6.03 10.8	0.02 0.14 0.18	0.02 0.14 0.18	6.55 21.6 25.5	Continuous	0 0 0	0 0 0
		Coverage, %	26.2	26.5	52.2	52.8	56.7	57.3	1.31	1.33	98.8	100	0	0
		Gaps, hr	0.03 8.42 60.2	6.07 9.61 60.2	0.03 3.01 48.2	0.03 3.41 48.2	0.03 3.76 10.1	0.08 4.52 10.1	0.03 10.5 270	1.78 10.5 270	0.02 0.25 0.78	0 0 0	No contact	No contact
Near	Mare Tranquillitatis	Contacts, hr	0.03 3.48 7.7	0.08 4.1 7.7	0.03 4.15 24.3	0.08 5.11 149	0.03 5 10.8	0.08 6.28 10.8	0.02 0.14 0.18	0.02 0.14 0.18	6.55 21.6 25.5	Continuous	0 0 0	0 0 0
		Coverage, %	29.5	29.9	56.2	56.9	57.2	57.8	1.29	1.3	98.8	100	0	0
		Gaps, hr	0.03 8.28 84.4	4.85 9.62 84.4	0.03 3.24 78.4	0.03 3.87 78.4	0.03 3.76 9.95	0.43 4.61 9.95	0.02 10.8 270	1.78 10.7 270	0.02 0.25 0.78	0 0 0	No contact	No contact
Limb	Mare Smythii	Contacts, hr	0.08 3.78 8.27	0.13 4.63 8.27	0.08 4.89 24.7	0.13 5.84 197	0.03 5.07 10.9	0.28 6.36 10.9	0.02 0.14 0.18	0.02 0.14 0.18	1.8 18.8 25.5	142 142 142	4.28 20.4 145	145 145 145
		Coverage, %	32.5	33	59.4	60.3	57.4	58.1	1.28	1.29	48	48.6	43.5	44.9
		Gaps, hr	0.03 7.87 108	4.12 9.47 108	0.03 3.36 96.6	0.03 4.2 96.6	0.03 3.77 9.55	0.45 4.63 9.55	1.78 10 272	1.78 10 272	0.02 16.2 148	148 148 148	0.02 22 181	181 181 181
Near	Oceanus Procellarum	Contacts, hr	0.03 4.43 8.62	0.23 5.19 8.62	0.03 6.23 148	0.13 7.74 233	0.03 5.24 10.8	0.08 6.38 10.8	0.02 0.14 0.18	0.02 0.14 0.18	2.58 20.3 25.5	219 219 219	1.07 19.3 30	59 59 59
		Coverage, %	35.5	35.7	62.8	63.2	57.6	58	1.28	1.29	75.1	75.9	17.6	17.7
		Gaps, hr	0.03 8 121	3.7 9.3 121	0.03 3.68 109	0.05 4.49 109	0.03 3.86 9.75	0.45 4.61 9.75	0.05 10 272	1.78 9.98 272	0.02 6.99 70.8	70.4 70.4 70.4	0.02 71.4 268	267 267 267
Limb	Orientale Basin	Contacts, hr	0.05 5.38 9.1	0.7 6.35 9.1	0.05 9.51 173	0.58 12.8 329	0.05 4.82 10.9	0.3 5.61 10.9	0.02 0.14 0.18	0.02 0.14 0.18	1.18 18.7 25.2	127 127 127	1.22 22.3 124	168 168 168
		Coverage, %	42.7	42.9	70.7	70.9	55.4	55.6	1.36	1.37	43	43.5	50.5	51.3
		Gaps, hr	0.03 6.78 121	3.1 7.96 121	0.03 3.51 116	0.03 4.67 116	0.03 3.87 10.4	0.05 4.46 10.4	0.02 9.46 268	1.78 9.46 268	0.02 19.3 163	162 162 162	0.02 24.3 158	158 158 158
Far	South Pole–Aitken Basin	Contacts, hr	0.03 6.2 9.35	0.03 8.04 9.35	7.07 29.7 149	Continuous	0.03 3.91 9.35	0.03 4.6 9.35	0.02 0.03 0.05	0.02 0.03 0.05	4.73 13.5 24.7	50.1 50.1 50.1	1.2 20.8 223	259 259 259
		Coverage, %	66.5	67.2	99.1	100	70.2	71	0.149	0.171	16.7	17.1	77.7	79.8
		Gaps, hr	0.03 3.12 5.17	0.13 3.93 4.97	0.03 0.27 0.68	0 0 0	0.03 1.66 4.67	0.13 1.88 4.67	1.92 17.4 585	1.92 16.6 581	0.02 53.5 239	239 239 239	0.02 6.77 67.6	67.6 67.6 67.6
Polar	South Pole	Contacts, hr	0.03 6.75 9.07	9.05 9.07 9.07	7.07 30.2 149	Continuous	0.03 4.05 9.07	0.48 4.77 9.07	0.02 0.18 0.18	0.02 0.18 0.18	2.13 15.5 24.9	93.5 93.5 93.5	0.27 20.3 221	224 224 224
		Coverage, %	74.8	65.6	99.1	100	78.8	79.6	8.92	9.02	31.3	32	67.3	69.4
		Gaps, hr	0.03 2.27 3.35	2.92 2.93 2.95	0.03 0.26 0.68	0 0 0	0.03 1.09 1.65	1.2 1.23 1.25	0.02 1.79 3.77	1.78 1.79 1.82	0.02 26.4 196	196 196 196	0.02 11.3 102	102 102 102

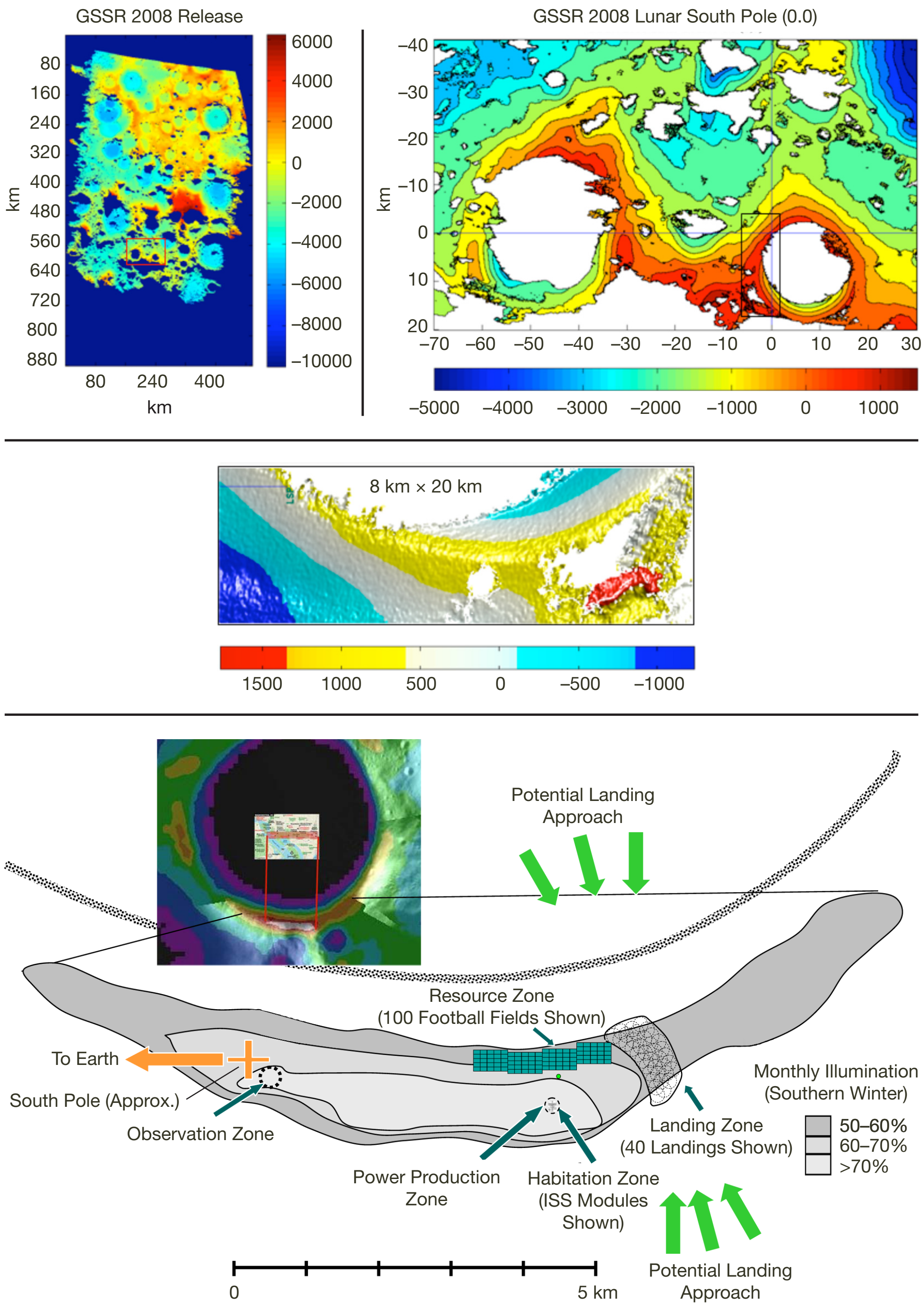


Figure 13. GSSR-released elevation map and NASA's future exploration site at the lunar south pole.

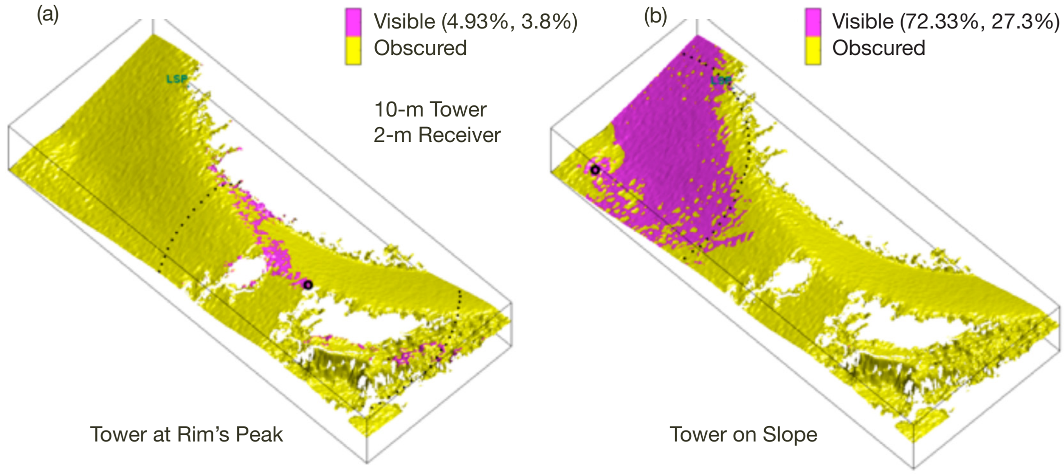


Figure 14. Line-of-sight coverage from a 2-m receiver to a 10-m tower stationed at (a) the peak and (b) on a slope of Shackleton Crater's rim.

the valley below becomes hidden over the cliff edge. One can interpret from Figure 14(a) that the peak area of interest at Shackleton Crater's rim is somewhat flat, and positioning the tower plays a very important role. Placing the tower appropriately — Figure 14(b) — can increase the area of LOS coverage.

To understand the sensitivity of the location of the tower, the percentage of coverage for the 8 × 20 km area was computed. The location of the tower is spaced uniformly every 800 m. The results are shown in Figure 15. One can see that the LOS coverage percent-

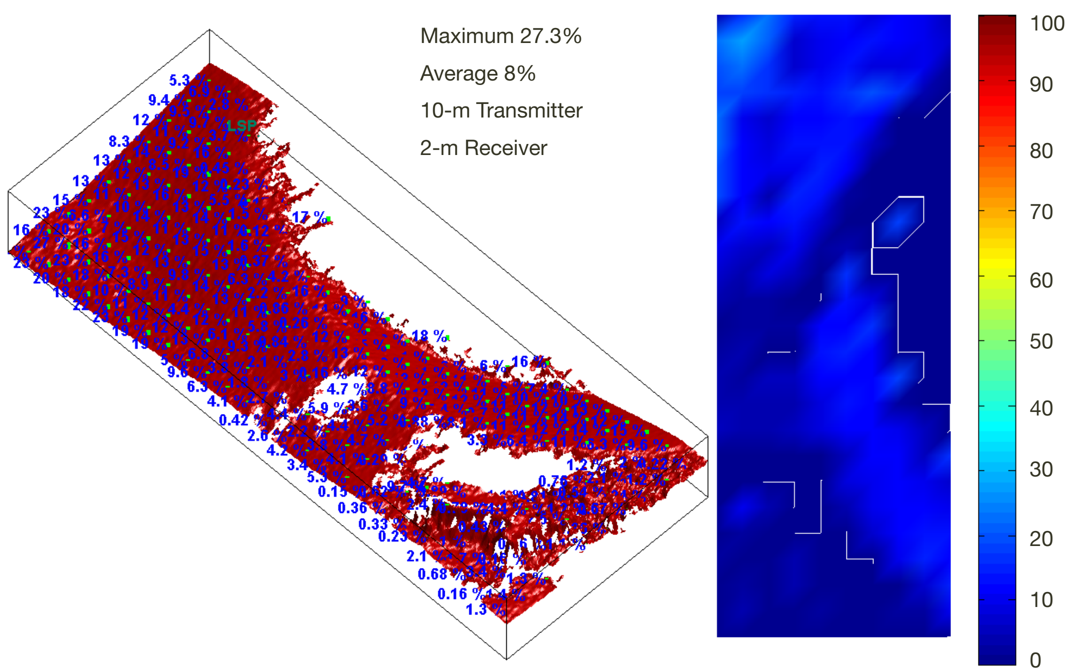


Figure 15. Percentage of line-of-sight coverage from 10-m tower to a 2-m receiver at Shackleton Crater's rim.

age is relatively low. On average, approximately 8 percent of the rectangle is covered and the maximum stays at 27.3 percent. As a result, the path loss in the surface-to-surface link budget should include not only the free space loss, but also the dominating diffraction and reflection losses. The lunar terrain will create a principal impact on the surface-to-surface communications due to the multipath effects. Significant degradation losses include the delay of the arrived signals, intersymbol interferences, multiple reflections, and diffraction of the signal. These losses and their uncertainties become even more severe in a crater or in rugged terrain. The impacts of terrain on lunar surface communications will be investigated in a future study.

Earth and Sun coverage for the peak at Shackleton Crater's rim is investigated next. The local coordinate frame is determined as follows: The x-axis is constructed by crossing its position vector with the north pole vector. The z-axis is the position vector, and the y-axis is found by completing a right-handed frame. Figure 16(b) shows the x and y axes. Earth is in the direction of the negative y-axis; in the positive y-axis stands a tall obstructing ridge, which limits the view to local regions. Figure 16(a) shows the viewable distance from the peak with a 10-m tower. Part of Mount Malapert, which is roughly 120 km from the south pole and 280 deg from the positive x-axis, can be seen from the tower. Notice that the local tall ridge, which resembles a protruding tooth, restricts most of the line-of-sight view from the positive x-axis up to the 120-deg line. Figure 16(c) depicts the horizon masks surrounding the peak with the heights of the tower at 2, 10, and 20 m. The azimuth resolution for calculating the horizon mask is 1 deg. The broken ellipses in Figure 16 distinctively emphasize the nearby tall ridge, which increases the horizon mask and reduces sunlight. The height of the tower plays an important role only when the obstructing objects are very near. The favorable impact of the tower height is a local phenomenon; the horizon masks remain relatively unchanged with respect to the height of the tower when the viewable distance is remote.

From the lunar south pole, Earth seems to slow-dance up and down the horizon in an oval path. The apparent size of Earth can vary as Earth can get as close as 363,000 km and as far as 405,000 km. Earth's lateral motion, due to the libration of the Moon, could span up to 16 deg. Precisely at the south pole, Earth can rise as high as 6.7 deg and set as low as –6.7 deg below its horizon due to the inclination of the Moon's orbit around Earth and the tilt of the Moon about its axis of rotation. In short, Earth appears to move in a confined box of dimensions 13.4 deg (vertical) by 16 deg (horizontal). Histograms of Earth's and the Sun's elevation angles from a peak at Shackleton Crater's rim are plotted in Figure 17(a) and (b), respectively.

The simulation was done for 18.6 yr at 15-min resolution. Since the peak of the proposed landing site is slightly off the south pole and toward the far side of the Moon, Earth's rise and set elevations are even lower. In other words, the ±6.7-deg band around the horizon containing Earth is shifted downward 0.4 deg, while the band around the horizon containing the Sun expands ±0.4 deg more. One should interpret from Figure 17 that, even though Earth and the Sun travel up and down in sinusoidal motion, the percentage of time for being at certain elevation angles is not uniform. In fact, Figure 17 indicates that, at this particular location, Earth tends to linger longer at the peaks and the dips, while the Sun spends more time at ±1.1 deg about the horizon. These may be more transparent when the trajec-

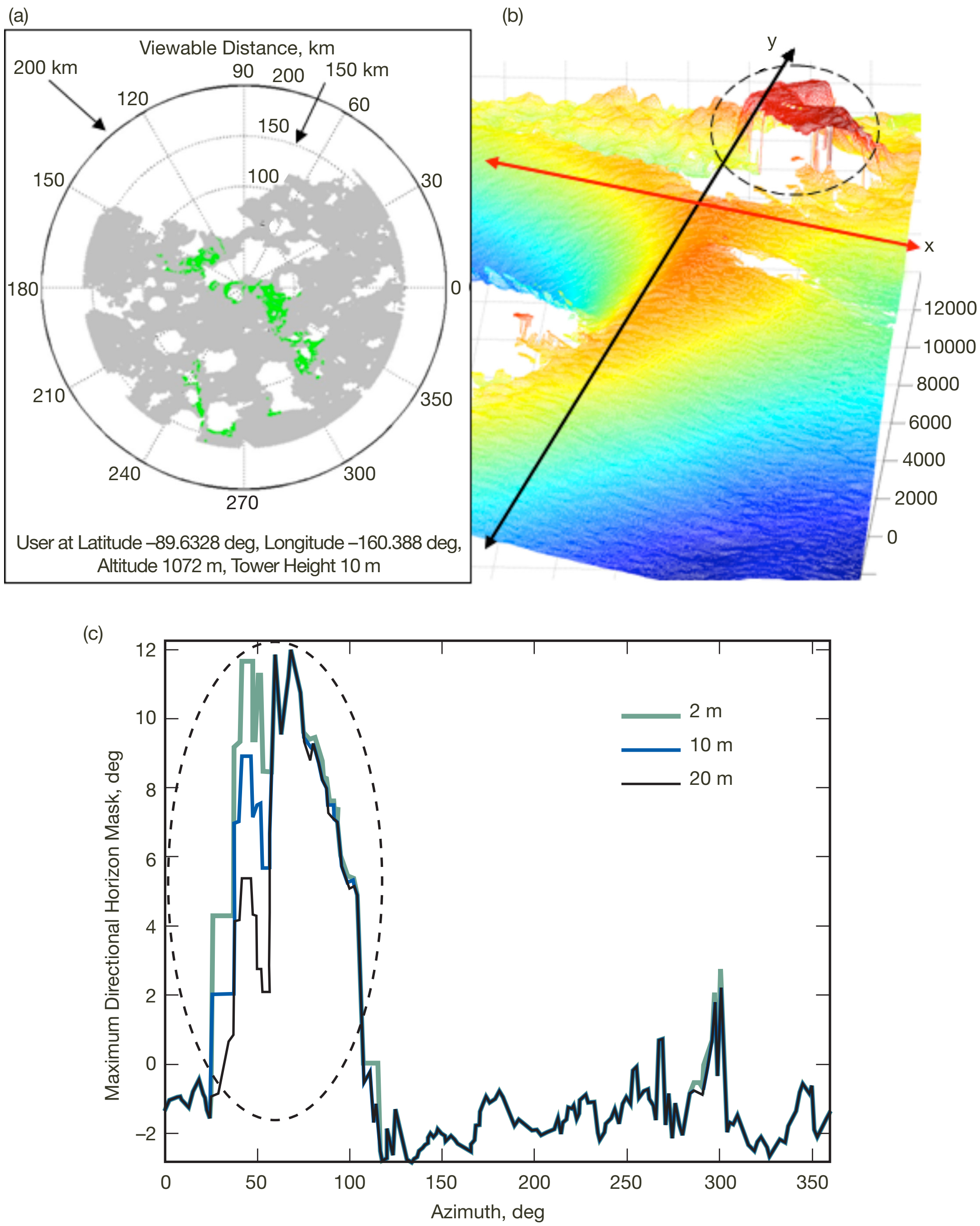


Figure 16. Viewable distance and horizon mask at the peak location on NASA's future exploration site near the lunar south pole.

tories of Earth and the Sun with respect to the local frame are observed — see Figure 18(a) and (b). To avoid overcrowding the graphs, only the first two years of simulation are shown in the figure. The dotted blue circles display the size of Earth, which could fluctuate from 1.8 deg to 2 deg. As one looks towards Earth from this location, the horizon mask varies between ±2 deg. When the center of Earth is above the local horizon mask, DTE communications may not be possible because an LOS path between the lunar south pole and northern sites on Earth, such as Madrid, Goldstone, or Usuda, may not exist. Thus, we assume that

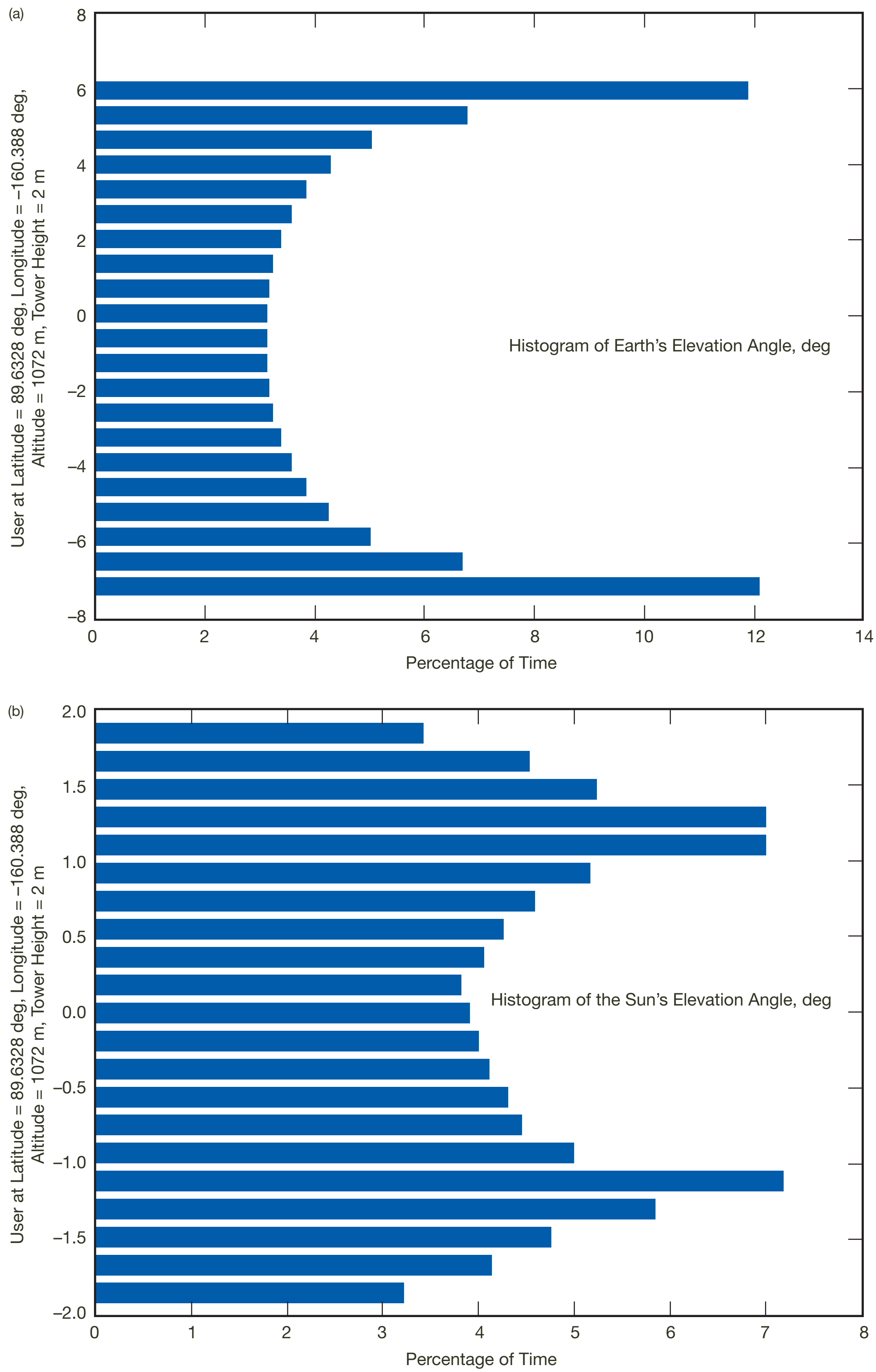
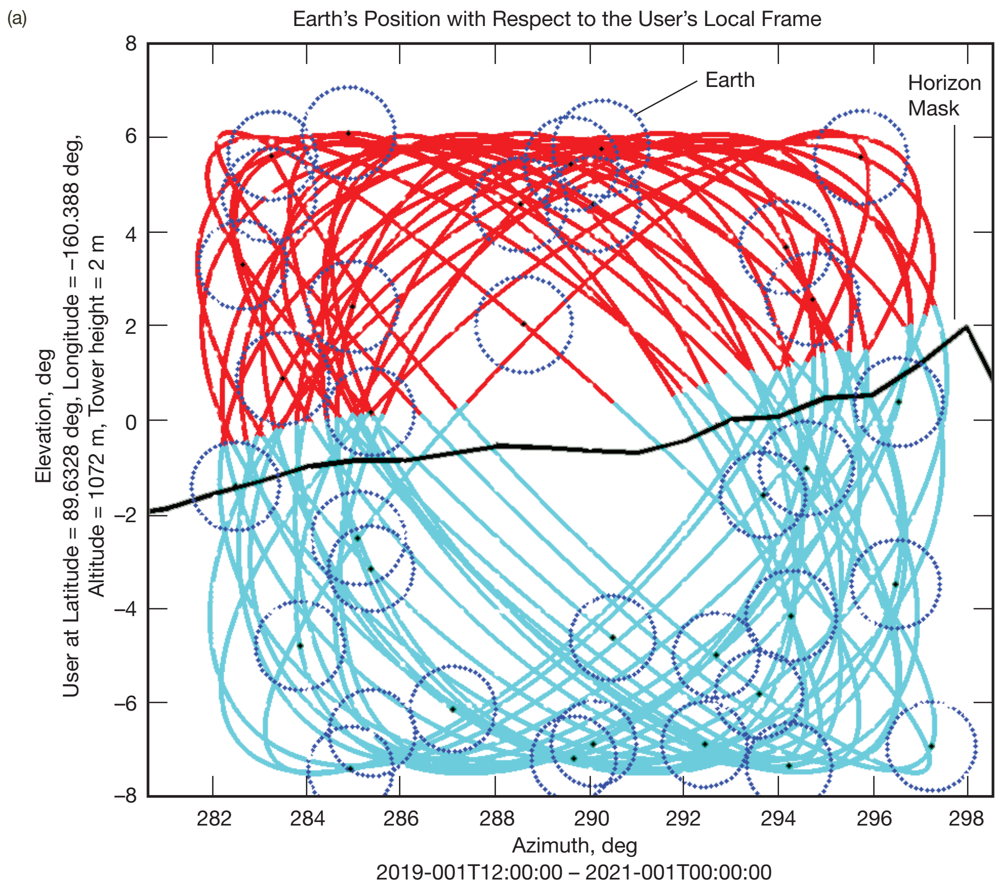


Figure 17. Percentage of time of (a) Earth's and (b) the Sun's elevation angles at a peak of Shackleton Crater's rim (18.6 yr at 15-min resolution).



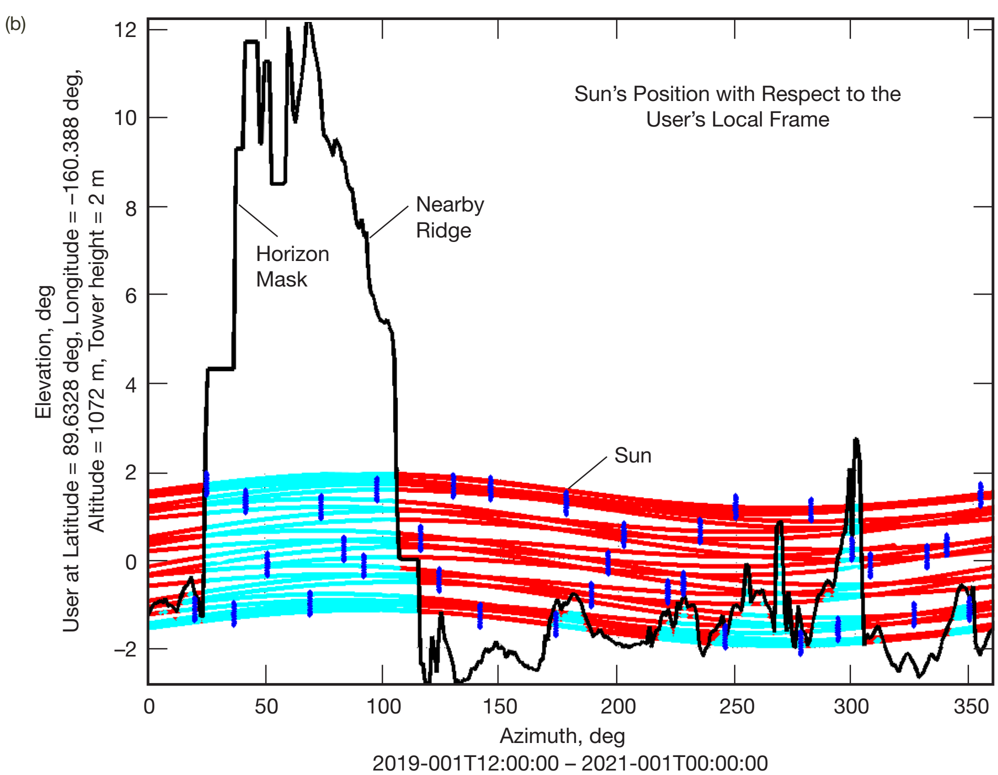


Figure 18. Two-year sample of (a) Earth's elevation, (b) the Sun's elevation, (c) Earth contacts, and (d) Sun contacts at a peak location on NASA's future exploration site near the lunar south pole.

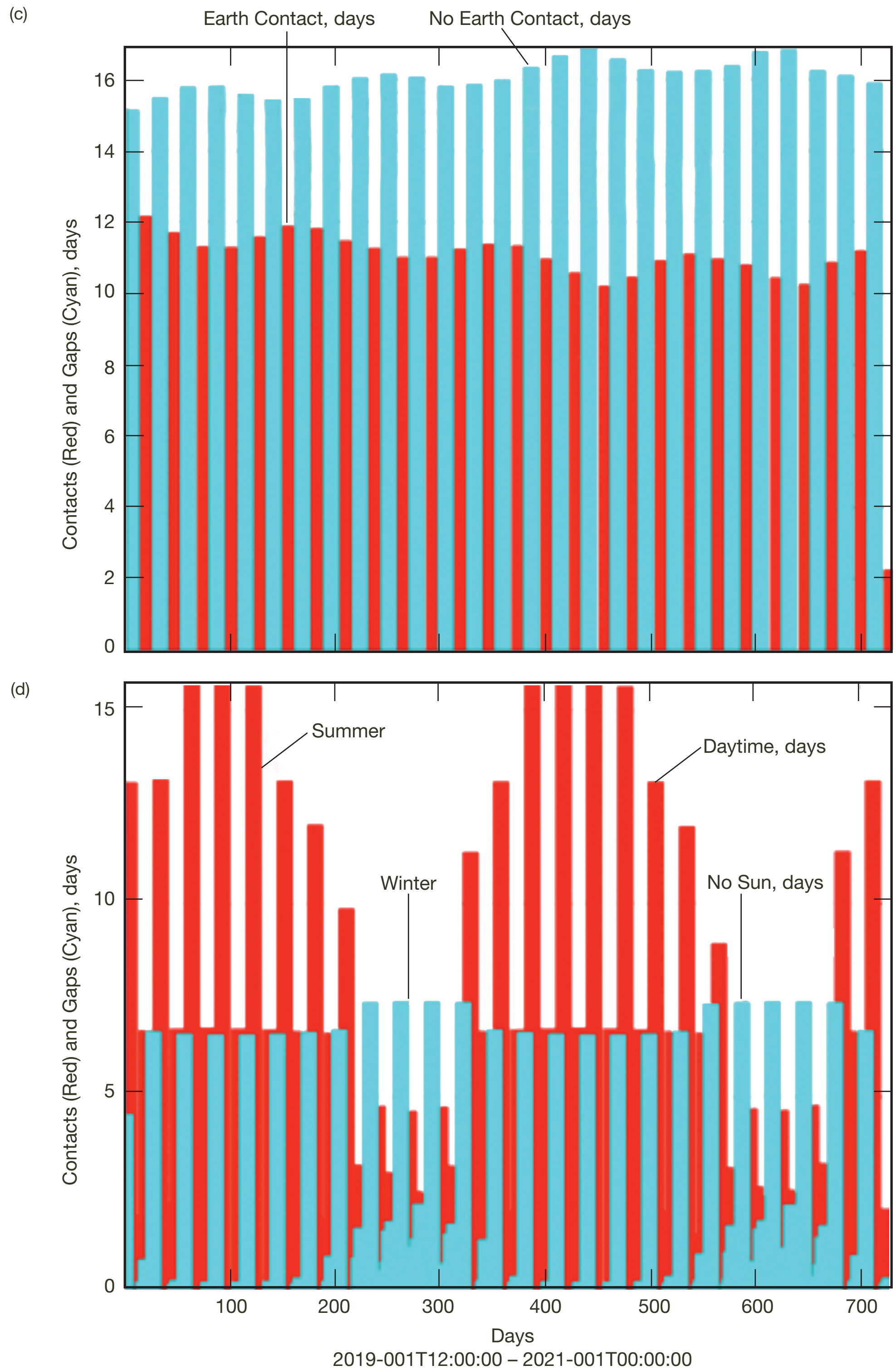


Figure 18. Two-year sample of (a) Earth's elevation, (b) the Sun's elevation, (c) Earth contacts, and (d) Sun contacts at a peak location on NASA's future exploration site near the lunar south pole.

communication to Earth is possible only when the entire Earth is above the horizon mask. The lower left section of Figure 18 shows the monthly contacts between the peak point on the rim of Shackleton Crater and Earth for 2019 to 2021. The red bars depict the durations of the contacts, whereas the light-blue bars show the communication gaps. It was found that the peak can communicate with Earth 44 percent of the time, and an average contact with Earth is approximately 12 days, with the longest contact being 13 days and the shortest contact being 10 days. More importantly, the average communication gap with Earth is 15 days, with the longest gap being 17 days and the shortest gap being 14 days. It was found that when standing on the Earth-facing slope of the rim of Shackleton Crater, the peak elevation and the height of the tower are not major contributing factors to contacts with Earth. Placing the communication tower on the near side of the Moon with clearance to the local horizon of the Earth-facing side can prolong the monthly contacts.

Figure 18(b) shows the position of the Sun with respect to the local frame at the peak of the rim. At the lunar south pole, the Sun circulates up and down in the sky within the ±1.54-deg band. Because the location of the peak is 0.4 deg off the pole, the Sun position actually gets expanded between –1.94 deg and +1.94 deg, making days or nights longer there depending on the season. The size of the Sun is approximately 0.5 deg. In this case, we assume solar panels are placed 2 m above the surface and that full illumination at the peak happens when the center of the Sun is above the local horizon. At this peak of the rim, it is sunlit approximately 67 percent of the time. The days could be as long as 16 Earth days and the longest night could be as long as 7.5 Earth days (due to the nearby ridge). Other solar blockages due to remote crests or edges are shorter and at most 2.5 Earth days.

In general, as soon as the solar panels deviate from the pole, the length of the day will become more fluctuant depending on the seasons. To stay sunlit permanently, the solar panels need to be at higher elevation, closer to the pole, and clear of any local obstructions. The length of the day or Earth contact can be prolonged by increasing the height of the tower. For example, to be able to see 1 deg below the horizon, the tower needs to be raised approximately 265 m, which may be challenging and costly. Locations for the Earth-pointing antenna and the solar panels at the lunar south pole can be optimized. However, the process can be computationally intensive for such a large terrain at fine resolution. We hope to study this question in detail and report on the results in a future article.

V. Summary

This article provides the coverage analyses between all possible communication nodes within lunar exploration. Communicating elements include the DSN, along with additional ground stations; the SN; the CEV on its round-trip journey to the Moon; the LRS in different orientations and constellations, including the halo orbits near the lunar libration points; and the 10 high-priority lunar landing sites proposed in *NASA's Exploration Systems Architecture Study*. We find that a combination of two TDRS (F-3 and F-9) can provide 90 percent same-hemisphere coverage for any spacecraft below 10,000 km in latitude. To achieve approximately 100 percent same-hemisphere coverage up to 10,000 km, three TDRS (F-3, F-8, and F-9) are required. In addition, handover between the SN and the DSN should occur at 10,000 km or more altitudes, where the same-hemisphere coverage of the SN starts to diminish and DSN6 (Canberra, Goldstone, Madrid, Hartebeesthoek, Santiago, and Usuda) coverage begins to reach 100 percent. DSN6 will not only provide consistently better coverage for the CEV than DSN3, but its coverage also does not depend on the trajectory path of the CEV or the mission timeframe. In addition, DSN6 can link continuously to Constellation A, Constellation B, and the halo relay satellites near the Earth–Moon libration points L1 and L2. Unless the CEV or the LRS are behind the Moon, DSN6 can always link to either one of them. The largest gap between DSN6 and the CEV is 47 min, and the LRS is 84 min. DSN6 can communicate with LRS 97.6 percent of the time and with CEV 73.2 percent of the time. When DSN6 is replaced with DSN3 (Canberra, Goldstone, Madrid), communication coverage with the lunar orbiting assets is reduced roughly 1 percent and at most 2 percent. Constellation B is the best option to provide both the store-and-forward and DBP relay coverage. Mainly, all ESAS 10 sites receive over 50 percent temporal coverage and the polar regions receive close to 80 percent of coverage.

It was found from the latest GSSR data that the terrain at the lunar south pole is rugged, and placing a lunar communication tower at the local peak of the rim does not necessarily yield the highest area of LOS coverage. Additionally, the surface-to-surface LOS view can be limited and thus the path loss in the surface-to-surface link budget should include not only the free space loss, but also the dominating diffraction and reflection losses. It was also found that when standing on the Earth-facing slope of the rim of Shackleton Crater, both the local elevations and the heights of realistic communicating towers do not lengthen the contacts with Earth. However, placing the Earth-pointing antenna toward the near side of the Moon would do so. Finally, to stay sunlit permanently at the pole, the solar panels need to be optimally placed at a local maximum that is closest to the pole. Algorithms will be developed in future studies to optimize the locations for the Earth-facing antenna, lunar-surface communication tower, and the solar panels, based on the latest terrain data. The unified theory of diffraction and ray tracing algorithms will be employed to characterize the diffractive and reflective multipath losses to investigate the impacts of terrain on lunar surface communications.

Acknowledgments

The authors wish to thank Hemali Vyas, David Heckman, Kristy Tran, Christian Ho, Todd Ely, Charles Ruggier, Martin Slade, and Clement Lee for the fruitful discussions, help, and suggestions.

References

[1] C. H. Lee, K-M Cheung, C. Edwards, S. J. Kerridge, G. K. Noreen, and A. Vaisnys, "Orbit Design Based on Global Maps of Telecom Metrics," *Proceedings of the IEEE Aerospace Conference*, Big Sky, Montana, March 5–12, 2005.

[2] C. H. Lee and K-M Cheung, "Communication-centric Spacecraft Design Optimization Tool and its Application to the Lunar Relay Satellite Design," *Proceedings of the IEEE Aerospace Engineering Conference,* Big Sky, Montana, March 1–8, 2008.

[3] NASA Goddard Space Flight Center, National Aeronautics and Space Administration, "Three Newly Designed Tracking and Data Relay Satellites To Help Replenish Existing On-Orbit Fleet," NASA Fact Sheet, FS-2001-9-025-GSFC, September 2001. http://www.nasa.gov/centers/goddard/pdf/97440main_TDRS_fs_9.18.pdf

[4] C. H. Lee and K-M Cheung, "Deep Space Network and Lunar Network Communication Coverage of the Moon," *Proceedings of the 57th International Astronautical Congress*, Valencia, Spain, IAC-06-B3.4.1, October 2006.

[5] C. H. Lee, "On the Optimal Extension of Ground Network Stations to Support NASA's Lunar Exploration," *Proceedings of the IEEE Aerospace Engineering Conference*, Big Sky, Montana, March 1–8, 2008.

[6] T. A. Ely and E. Lieb, "Constellations of Elliptical Inclined Lunar Orbits Providing Polar and Global Coverage," *Proceedings of the AAS/AIAA Astrodynamics Specialists Conference*, AAS-05-343, Lake Tahoe, California, 2005.

[7] M. Flanegan, M. Mesarch, J. Gal-Edd, D. Peters, B. Shah, C. H. Lee, A. Vaisnys, T. Ely, S. Ploen, J. Freeh, and S. Oleson, "Small Satellite Implementation of a Lunar Relay Satellite," presented at the *21st Annual AIAA/USU Conference on Small Satellites*, Logan, Utah, August 13, 2007.

[8] K. Hamera, T. Mosher, M. Gefreh, R. Paul, L. Slavkin, and J. Trojan, "An Evolvable Lunar Communication and Navigation Constellation Concept," *Proceedings of the IEEE Aerospace Engineering Conference*, Big Sky, Montana, March 1–8, 2008.

[9] K-M Cheung, K. Kellogg, C. H. Lee, F. Stocklin, D. Zillig, and K. Fielhauer, "Architecture Study on Telemetry Coverage for Immediate Post-Separation Phase," *SpaceOps 2008*, American Institute of Aeronautics and Astronautics AIAA-2008-3234, Heidelberg, Germany, May 12–16, 2008.

[10] S. Hensley, E. Gurrola, P. Rosen, M. Slade, J. Jao, M. Kobrick, R. Jurgens, E. De Jong, and B. Wilson, "Radar Generates High-Resolution Topographic Map of the Moon," Society of Photo-Optical Instrumentation Engineers, June 2008. http://spie.org/x25472.xml

[11] J. Schier, M. Flanegan, L. Anderson, T. Ely, C. H. Lee, and B. Shah, "NASA Lunar Architecture Team (LAT) Communication and Navigation Architecture," *SpaceOps 2008*, American Institute of Aeronautics and Astronautics AIAA-2008-3589, Heidelberg, Germany, May 12–16, 2008.